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TITANIUM COATING IGNITION TEST

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20. Abstract *(Continue on reverse side if necessary and identify by block number)*

The objective of this program was to test the capability of state-of-the-art coatings to minimize self-sustained combustion and eliminate downstream propagation under environmental conditions typical of those present in current gas turbine engine compressors. Two kinds of coatings at different thicknesses were applied to two different titanium alloys and subjected to cascade (molten metal ignition) combustion testing. These tests resulted in 27 combinations using three pressures, three temperatures, and three air velocities. It was noted that burn severity and chordwise burn velocity were significantly affected by chamber air pressure and air velocity parameters. The presence of a coating decreased burn severity.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SUMMARY

The objective of this program was to test the capability of state-of-the-art coatings to minimize self-sustained combustion and eliminate downstream propagation under environmental conditions typical of those present in current gas turbine engines. The coating systems tested are those resulting from all combinations of the following:

Coatings: Pt/Cu/Ni and Aluminum
Alloys: Ti 8Al-1Mo-1V and Ti 3Al-6Cr-8V-0.4Mo-4Zr

Each coating system and baseline (uncoated) were subjected to cascade (molten metal ignition) combustion testing according to a 3 pressure by 3 temperature by 3 air velocity environmental matrix. This test plan resulted in 288 tests being conducted.

An increase in air pressure, determined to be the most significant variable, produced an increase in burn severity. Also, the presence of a coating on the specimen resulted in a decrease in burn severity, and as coating thickness increased burn severity decreased.

The chordwise burn velocity (CBV) increased with an increase in air pressure or air velocity. On a Ti 8Al-1Mo-1V substrate, coating type did not affect CBV, but an increase in coating thickness resulted in a lower CBV. On a Ti 3Al-6Cr-8V-0.4Mo-4Zr the Pt/Cu/Ni coating produced CBV values significantly lower than the IVD aluminum coating.

SECTION I

INTRODUCTION

The rapid development of high-performance aircraft gas turbine engines has necessitated corresponding advances in materials technology. Included in these advances are titanium alloys for fan and compressor components. These have contributed to gains in performance and efficiency because of their high strength and low density, resulting in favorable strength-to-weight ratios. Titanium alloys have gained wide acceptance and are currently being used at operating temperatures up to 900°F (482°C). Typical components made of titanium include static structures such as fan and compressor vanes and cases, and rotating components such as fan and compressor disks and blades.

Titanium, like several other metals, can be made to ignite and react in a rapid oxidation (exothermic) process. In the specific case of titanium, the reactivity is enhanced by a unique combination of thermophysical properties including a high heat of combustion, a low thermal conductivity, and a spontaneous ignition temperature below its melting point. This latter property favors ignition rather than melting, thus producing additional rapid local temperature increases and rapid propagation of the resultant combustion once ignition occurs.

Several instances of titanium blade and vane ignition and combustion have occurred in gas turbine compressors over a wide range of ambient pressures and temperatures. Initiating conditions may include tip rubbing on the adjacent casing, blade/structure rubbing as a result of compressor stalls (blades deflect into the casing), rotor imbalance, entrapment of broken airfoil elements, and aircraft maneuvers. Aerodynamic heating of compressor components during a stall also has been established as the cause of ignition of titanium gas turbine components. Improved compressor seals have helped to reduce the blade tip-rubbing problem. However, the high-velocity airstream in axial-flow compressors enhances the continued combustion of any titanium blade or vane that does ignite, and causes burning particles and molten metal to be sloughed off. These particles can be entrained in the airstream and impinge on downstream components, thereby spreading combustion. The results and extent of this spreading depend largely on the environmental conditions prevalent at the time of ignition, and can vary from burning the tips of a few compressor blades, as illustrated in Figure 1, to the catastrophic destruction of an entire engine.

When the frequency of titanium fires showed a marked increase in 1970, an analytical study was initiated to define the gas turbine conditions conducive to sustained combustion. The initial analytical study was a titanium combustion model that defined a combustion limit above which fires were sustained and below which they were not. The model was based on the cause of fires at that time and established combustion limits in terms of air temperature and compressor blade leading-edge Reynolds number. The compressor blade leading-edge Reynolds number for a given stage is a function of pressure, airstream velocity, and blade configuration. When the environmental conditions of the compressor vane stage of a typical GTE are compared with this initial Model, the limit (stage) of utilization of a given material will be dependant on the combustibility properties of that material.

Figure 2 illustrates the manner in which this Model could be used to predict performance of a given alloy-coating system in a hypothetical gas turbine engine compressor.

As the compressor stage number increases, the blades are both hotter and have a higher leading edge Reynolds number (partly because of the accompanying increased pressure). This is illustrated by the "compressor condition" curve in Figure 2.

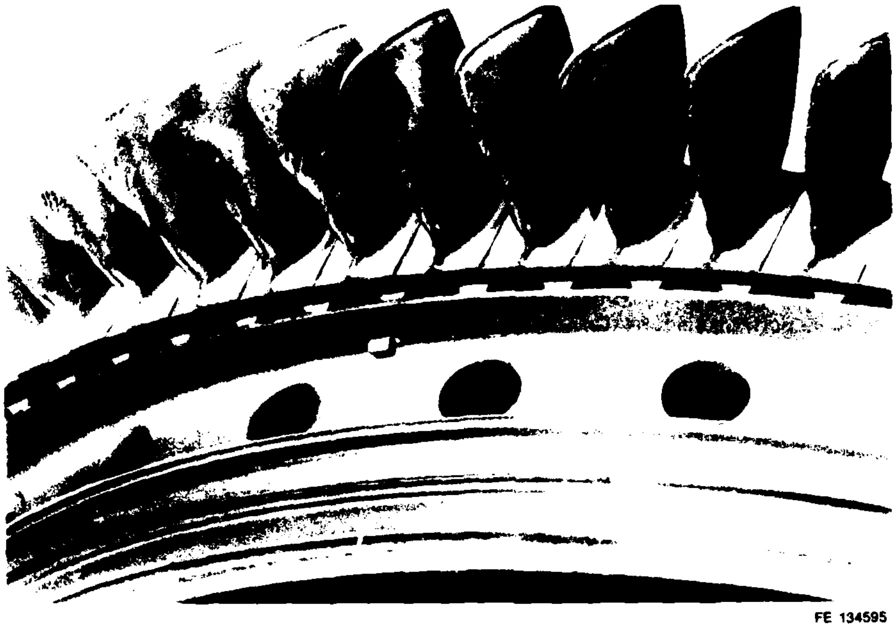


Figure 1. Compressor Blades in Gas Turbine After Minor Titanium Fire

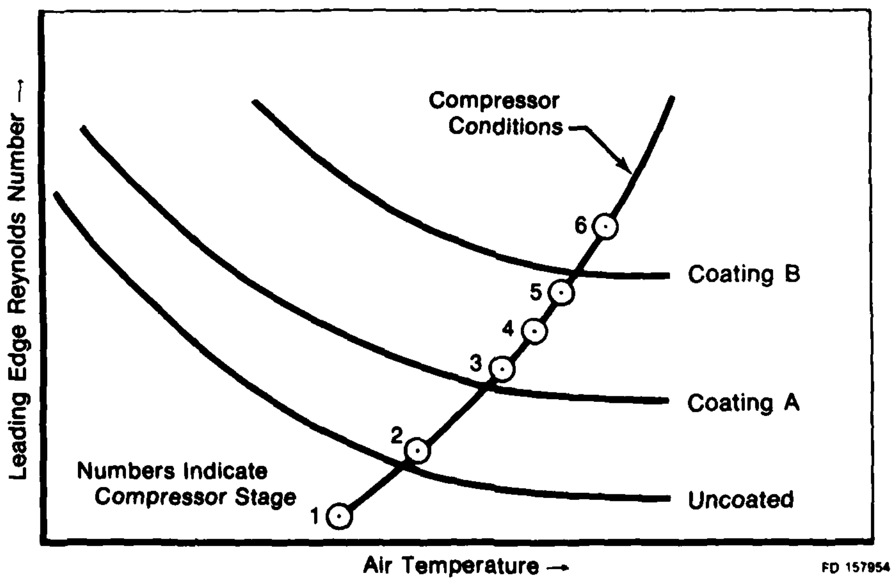


Figure 2. Predicted Combustion Limits for Coated Titanium

From the combination of the "compressor condition" curve and the sustained combustion curve for uncoated Ti, we can conclude that uncoated Ti can be used in the 1st-stage of our hypothetical compressor. However, if used in stages 2 through 6 ignition will occur and the fire will be sustained causing considerable damage.

Coating the titanium alloy has improved resistance to sustained combustion (Reference 5). If coating "A" raises the sustained combustion curve then using the same logic, the coated titanium may be used in stages 1 and 2. However, if used in stages 3 through 6 sustained combustion would cause considerable damage. In the example shown in Figure 2, the "B" coating on titanium allows its use through compressor stage 5.

The objective of the program described in this report was to test the capability of state-of-the-art coatings to minimize self-sustained combustion and eliminate downstream propagation under various gas turbine engine compressor conditions.

SECTION II

TITANIUM IGNITION AND COMBUSTION TESTS

TEST MATERIALS AND CONDITIONS

Materials

Coatings

This program was initially planned to involve a detailed study of the ignition and combustion characteristics of four coatings on a titanium alloy at two application thicknesses over a wide range of environmental conditions.

Selection of the specific coatings employed was based on results of combustion and high-cycle fatigue (HCF) screening tests performed on a similar, concurrent NASA contract, NAS3-21815 (Reference 2). This test program subjected 15 different coatings to a CO_2 laser ignition source with subsequent evaluation of the severity of combustion propagation. In addition, this initial screening test included limited HCF testing of the candidate coatings to assess the influence of the coating on this important physical property parameter.

Two of the coating systems selected for this program as a result of the screening phase of the NASA program were:

Coating Composition	Application Thickness, mm (in.) A	B
IVD Aluminum	0.05 (0.002)	0.08 (0.003)
Pt/Cu/Ni		
Platinum	0.001 (0.00004)	0.001 (0.00004)
Copper	0.05 (0.002)	0.10 (0.004)
Nickel	0.01 (0.0003)	0.01 (0.0003)

Two additional coating systems were required to complete the number needed to perform this program. The screening test results, however, did not yield two additional coatings having prospects of significantly reducing sustained combustion. For this reason, therefore, the Air Force Project Manager redirected the program by substituting a second titanium substrate alloy for the additional two coatings.

Following the analysis of results of tests conducted with the above coating systems, additional limited testing was conducted on uncoated TiAl alloy and Ti 8Al-1Mo-1V specimens with the following coating:

Coating Composition	Application Thickness, mm (in.)			
Copper/Aluminum				
Cu	0.05 (0.002)	0.11 (0.0043)	0.14 (0.0055)	0.20 (0.008)
Al	0.05 (0.002)	0.005 (0.002)	0.05 (0.002)	0.05 (0.002)
Nickel/Aluminum				
Ni	0.05 (0.002)	0.10 (0.04)	0.15 (0.006)	
Al	0.05 (0.002)	0.05 (0.002)	0.05 (0.002)	

Substrate Alloys

Titanium alloy Ti 8Al-1Mo-1V was selected originally as the substrate material upon which to evaluate the test coatings. This alloy was selected for use in this coating study because it is representative of alloys used in gas turbine engines in applications which have experienced ignition and sustained combustion. In addition, Ti 8Al-1Mo-1V has been used extensively in past combustion studies and thus, considerable data was available to supplement the effect produced by a coating.

The second titanium alloy substrate employed in this program was Ti 3Al-6Cr-8V-0.4Mo-4Zr. This alloy was substituted for the two additional coating systems as pointed out (above) because previous limited testing by the Air Force had indicated that it was not subject to sustained combustion to the extent experienced by other more common titanium alloys.

Test Specimen Configuration

Test specimens for coating application were prepared from the test alloy sheet stock by shearing to a nominal 1.0 by 3.0 in. (2.5 by 7.6 cm) dimension. The Ti 8Al-1Mo-1V sheet stock resulted in a specimen thickness range from 0.059 to 0.061 in. (1.50 to 1.55 mm) whereas the available Ti 3Al-6Cr-8V-0.4Mo-4Zr sheet stock produced specimens varying from 0.050 in. to 0.055 in. (1.26 to 1.39 mm). For subsequent data analysis involving specimen dimensions, actual measured values were used.

The planned test concept involved the laser ignition of an uncoated Ti 8Al-1Mo-1V igniter specimen upstream of and in line with the coated test specimen (Figure 3A). The quantity of molten titanium produced by this 1-in.-wide by 0.06-in.-thick igniter, however, proved to provide far too severe a combustion reaction to permit distinguishing between the effect of coating and/or test environment.

Successive iterations were made to alter the igniter configuration in an attempt to reduce the severity of the ignition source. This igniter configuration optimization study employed as the evaluation standard the damage inflicted on a downstream specimen of Inconel 718. Since this alloy is used in compressor vane and case assemblies, the coating sought should protect Ti 8Al-1Mo-1V so it experiences no more damage than the Inconel 718. The igniter configuration shown in Figure 3B produced $<5\%$ burn damage to the Inconel 718 and was the most promising one tested. This configuration produces sufficient molten material to ignite all uncoated specimens tested. In addition, it eliminates the occasionally observed tendency of full length igniters to separately ignite the test specimen near the top and bottom, thereby cutting out an unburned segment in the middle.

Environmental Test Conditions

The overall program test concept was to evaluate candidate coatings at various environmental conditions typically found in gas turbine engine compressors. Upon analyzing the environmental conditions found in current high-performance gas turbine engine compressors, the following ranges of test parameters were established for this program:

Temperature °C (°F): T_1 = 316 (600); T_2 = 385 (725); T_3 = 441 (825)

Pressure MPa (psia): P_1 = 0.28 (40); P_2 = 0.41 (60); P_3 = 0.55 (80)

Velocity m/sec (ft/sec): V_1 = 183 (600); V_2 = 244 (800); V_3 = 305 (1000)

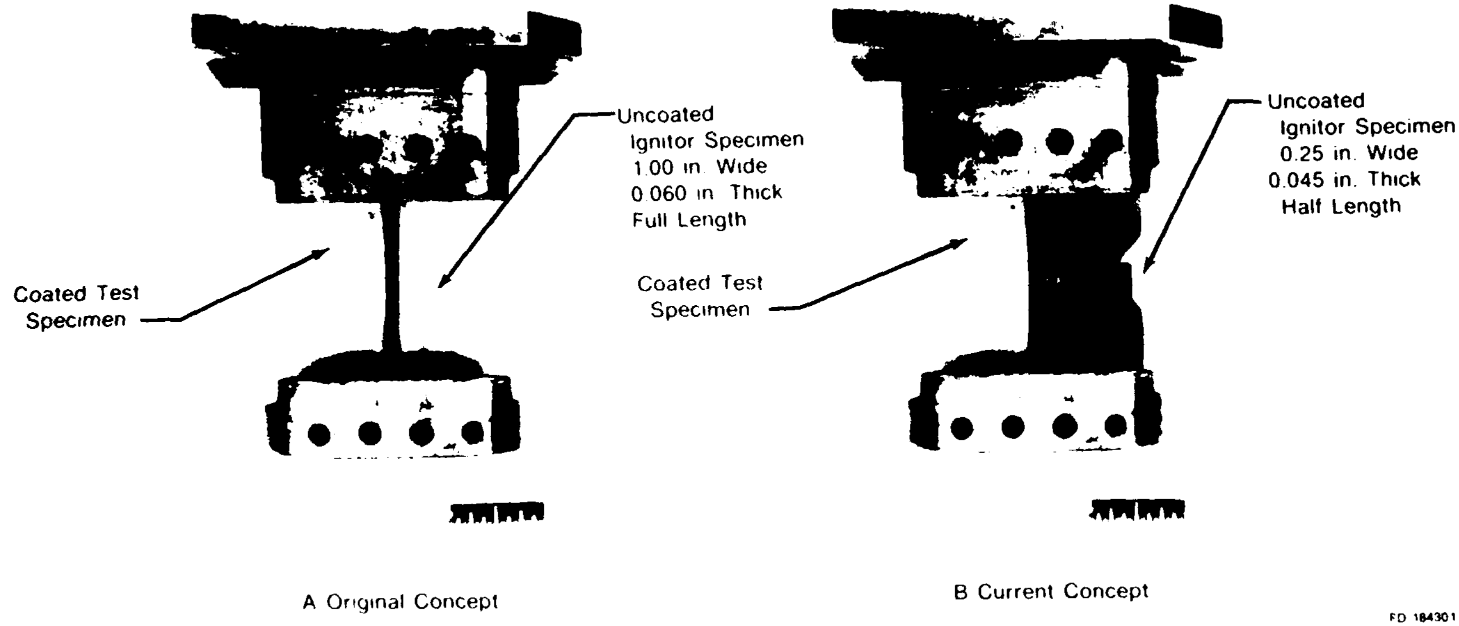


Figure 3. Igniter Specimen Configurations

These conditions encompass those found in compressor stages which are the most logical candidate for coated titanium rotor and/or stator applications.

Environmental test conditions selected for the additional limited tests were:

Specimen	Temp °C (°F)	Pressure MPa (psia)	Velocity m/sec (ft/sec)
TiAl	316 (600)	0.55 (80)	244 (800)
	316 (600)	0.62 (90)	244 (800)
	316 (600)	0.69 (100)	244 (800)
Coated Ti 8-1-1	316 (600)	0.42 (60)	244 (800)

TEST PLAN

The large number of possible tests resulting from an evaluation of two coated and one uncoated specimens on two substrate alloys in a 3 by 3 by 3 environmental matrix offered an excellent opportunity to use a statistical test plan designed for an analysis of variance solution. Such a factorial experiment would permit identification of any existing first and higher order parameter interactions.

The test matrix employed was designed to eliminate the need to conduct duplicate tests for the coated and uncoated specimens at 18 of the 27 environmental conditions. The tests eliminated for each coating were replaced with specimens having an increased coating thickness.

The environmental matrix used was:

		Pres	Temperature T_1	T_2	T_3
Gas Path Velocity	V_1	P_1	R	X	X
		P_2	X	X	R
		P_3	X	R	X
	V_2	P_1	X	X	R
		P_2	X	R	X
		P_3	R	X	X
	V_3	P_1	X	R	X
		P_2	R	X	X
		P_3	X	X	R

Note: Environmental parameters and subscripts are as defined under Environmental Test Conditions above.

Specimens tested in each block of this matrix were as follows for each substrate:

X = One observation for substrate baseline; one observation for each of the two coatings at application thickness A; and one observation for each of the two coatings at application thickness B.

R = Two observations for substrate baseline; and two observations for each of the two coatings at application thickness A.

This test plan required conducting 288 combustion tests.

TEST FACILITIES

The P&WA/GPD titanium combustion test rig is a small wind tunnel driven from a 350 psi compressed air supply. Ancillary conditioning equipment permits the simulation of a wide range of environmental combinations of air pressure (up to 1.25 MPa (180 psia)), temperature (up to 455°C (850°F)), and airstream velocity (up to 305 m/sec ('000 ft/sec)). Small test specimens are mounted in a rectangular test chamber. Instrumentation is provided to determine pressure and temperature at strategic locations in/on the rig.

The overall arrangement of the test rig is shown in Figure 4.

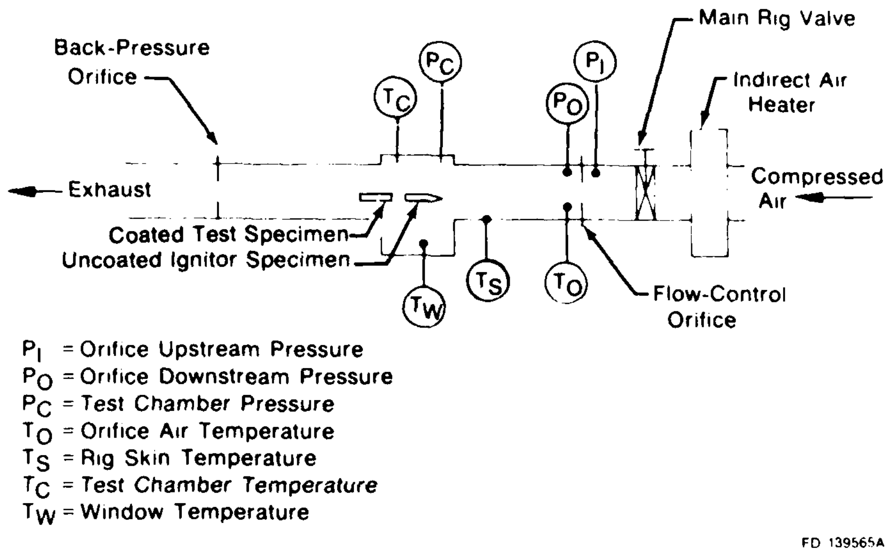


Figure 4. Titanium Combustion Test Rig

Air, supplied from a large compressor, is passed through a gas-fired indirect heater and a flow-measuring orifice prior to entering the test section. The test section, shown schematically in Figure 5, is a 19.1 mm by 50.1 mm (0.75 in. by 2.0 in.) rectangular channel with a bellmouth inlet and 75 mm (3.0 in.) of straight section upstream of the airfoil leading edge. The test specimens mount in a cylindrical carrier which is inserted into the test section. Orifice plates, upstream and downstream of the test section, provide control of the flowrate and pressure level. Thermocouples are positioned to provide temperatures at the flow-measuring orifice, in the specimen test chamber, on the rig skin, and at the laser and camera windows. Airstream flow is determined by calculation using the differential pressure (ΔP) across the orifice.

The test section has two windows: one for laser irradiation of the specimen and one for photographic viewing of the test specimen. These windows are mounted in a port on the side of the rig approximately 20.3 cm (8 in.) from the test specimen. The window for the camera is fused quartz which is 63.5 mm (2.500 in.) in diameter and 12.7 mm (0.500 in.) thick. The laser beam window is 38.1 mm (1.500 in.) in diameter and 6.35 mm (0.250 in.) thick zinc selenide. This material offers excellent transmissivity for the 10.6-micron wavelength emission of the CO laser beam. The zinc selenide window has an antireflective coating on both faces to minimize reflection and scatter of the beam. The quartz window has excellent optical clarity for visible light but it will not transmit the CO laser light, thus protecting the camera lens from scattered reflections of the laser beam. The windows are protected from the

high-temperature test environment by a water jacket to absorb conducted heat in the metal housing and an air injection system to film-cool the optical surfaces. In addition, a remotely operated metal cover protects the zinc selenide from the hot air flowing through the rig.

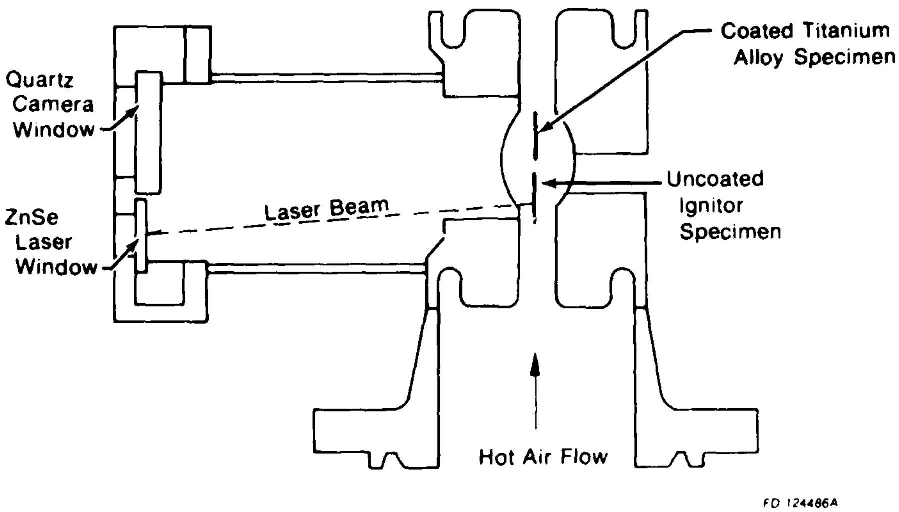


Figure 5. Titanium Combustion Rig Test Section

The arrangement of the test section and other supporting test equipment is shown in Figures 6 and 7. Because of environmental requirements, the laser equipment is located in the air-conditioned control room and the beam passed through a port in the wall. A high-speed Hycam motion picture camera and a video camera with a tape recording/playback system are arranged, through the use of a beam splitter, to permit simultaneous photographic recording and real-time video observation. The energy required for specimen ignition is supplied by a CRL Model 41 laser. This electric discharge, water-cooled CO laser system is capable of providing an output of approximately 250 watts in the TEM 00 mode at a transmission frequency of 10.6 microns.

The beam is defocused at the specimen to a diameter of approximately 2 mm to yield an incident average power density of approximately 2.5 Kw/cm absorbed by the specimen. A coincident helium-neon laser is used to provide a visible red beam for alignment of the hot CO laser beam on the titanium airfoil. This red alignment beam is observed using the videotape system.

In this program, coated test specimens were subjected to a molten metal ignition source. The coated specimen was located in line with, and approximately 19 mm (0.75 in.) downstream of an uncoated Ti 8Al-1Mo-1V specimen. The uncoated specimen was ignited by the laser source. Molten metal carried in the airstream from the burning specimen comprised the ignition source for the downstream coated specimen.

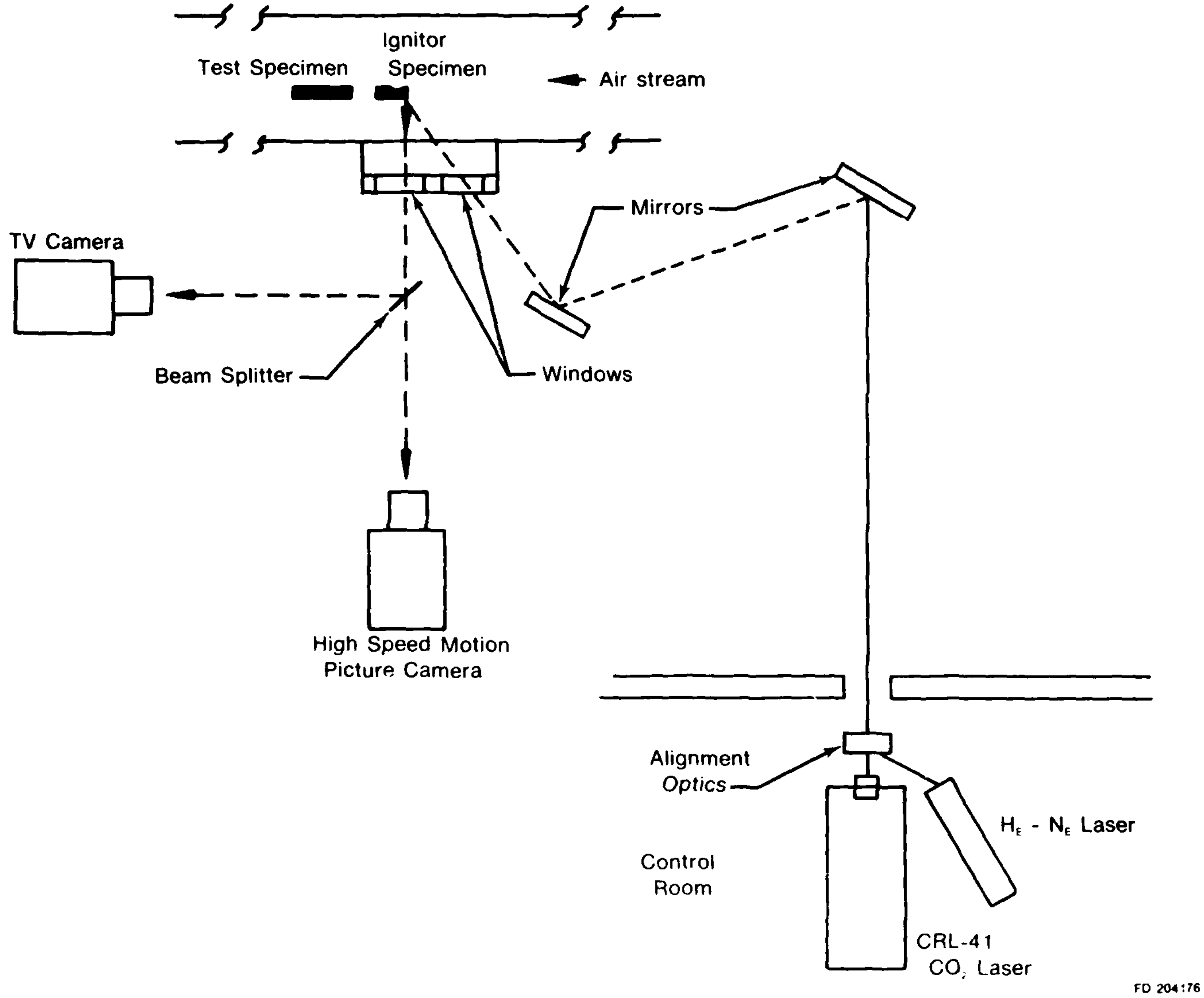


Figure 6. Arrangement of Laser Ignition and Photographic Recording Systems

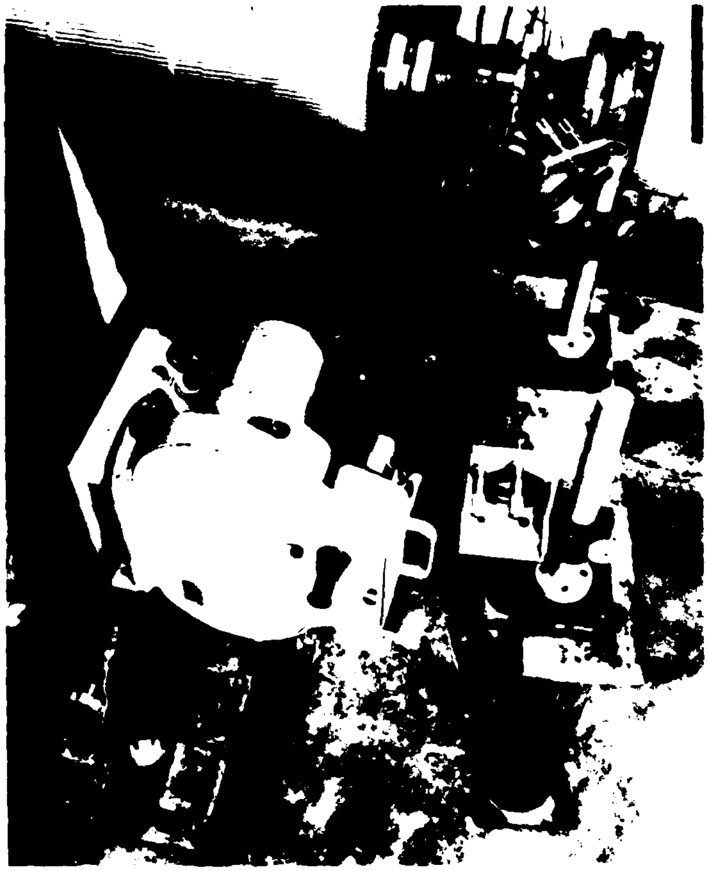


Figure 7. Titanium Combustion Test Rig Setup

TEST RUN PROCEDURE

The optimized test sequence employed on this program evolved from experience gained during several previous test programs.

Prior to a test run, the test specimen and igniter specimen were secured in the specimen holder. A distance of 1.91 cm (0.75 in.) between the test and igniter specimens was maintained by the use of a template. The use of two specimen holders permitted the preparation of one specimen holder while the specimens in the other holder were being tested, thereby increasing test time efficiency. Individual run values for air velocity and chamber pressure were established by installing a specific combination of flow-measuring and backpressure orifices in the test rig. After setting the heater to the desired temperature, airflow was introduced into the system and the test chamber allowed to come to thermal equilibrium. At thermal equilibrium, the laser optics were aligned using the visible helium-neon laser beam and the videotape system. Specimen illumination during alignment was provided by a high-intensity light transmitted from its source by fiber optics. For high-speed photographic coverage, the camera was focused on the specimen at all times during the run. Light from the specimen ignition and burning was sufficiently intense to permit photodocumentation of burn propagation and melt transportation. An event marker (light pulse) was recorded on the side of the film on all runs to annotate the start and finish of the laser action during the run. The high-speed films were also marked with light pulses from a 1000 Hz timing generator to provide an absolute time reference for event sequences.

Just prior to the start of a run, final temperature and pressure adjustments were made by judicious throttling of the hot air valve and a cold air bleed input valve. Simultaneously, a final adjustment, if required, was made to the laser alignment. Final run parameters were then recorded and the test initiated by a time-sequenced switch which, when actuated, started the high-speed camera. Approximately 1.5 sec after camera start, the sequencer opened the shutter protecting the ZnSe window. After an additional 0.5 sec, the sequencer opened the laser shutter to irradiate the specimen, thereby starting the run. The laser remained on for 5 sec before the sequencer closed the laser shutter, then the combustion rig shutter. This time sequence was manually overridden when ignition occurred before the 5 sec had elapsed. The camera was allowed to run out of film (about 16 sec) and was sequenced off at approximately 20 sec. The video system remains on at all times in a CCTV mode. Videotape recording was controlled manually during a run sequence. The instant replay and slow motion/stop frame capability of the color video recording permitted immediate review of the test run for its potential impact on the next test run.

SECTION III

TEST RESULTS AND ANALYSIS

This section begins with a detailed description of the procedure used in acquiring the various combustion parameters subsequently used as the basis for an analysis of the observed test performance. This is followed by an assessment of the accuracy of the primary and derived data obtained during the course of the program. The final subsection presents an analysis of test results in terms of the effect of specimen substrate alloy, coating composition, coating thickness, and test environmental conditions.

DATA ACQUISITION PROCEDURE

This subsection contains a detailed description of the procedures used in converting the basic raw data into forms suitable for use in the subsequent analysis and interpretation of test performance.

Test program data emanated from three sources; test chamber environmental conditions, the specimen itself, and the high-speed film coverage of the test run.

Test Run Data

Test chamber environmental temperature and pressure data, recorded just prior to the test run, served only to permit calculation of airstream velocity and to verify compliance with the established run parameters. This test run environmental data is included in Appendices A, B and C.

Burn Severity Data

Data for the determination of burn severity was obtained by photographing the reconstructed specimen (printed at approximately 3X) to determine the area burned. Because of the heat-sink effect at the ends of the specimen holder, only the 53.3 mm (2.10 in.) exposed portion of the specimen was considered in this determination. This enlarged photo was then taped to the Data Analyzer screen, and measurements made using the sonic digitizer pen. A TTY printout of these measurements, together with their use, is illustrated below with points referenced in this discussion shown in Figure 8.

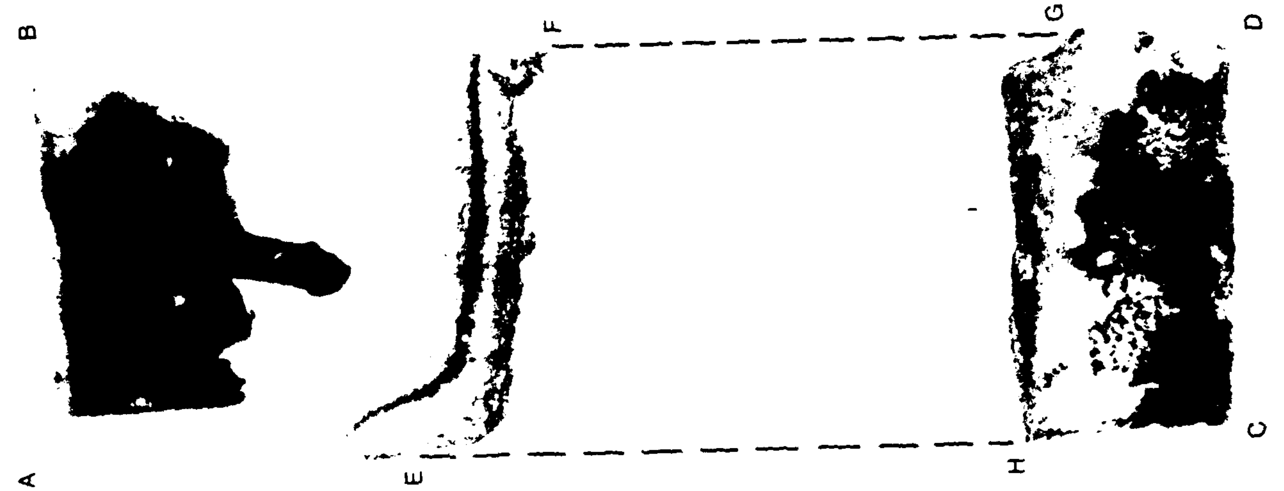
	Area**	
1	A = 23.096 sq in	Specimen total area (area bounded by ABDC)

	Area**	
2	A = 9.33867 sq in	Triplicate determination
3	A = 9.35482 sq in	of burned area (area bounded
4	A = 9.29305 sq in	by tracing EFGH)

Measurement 1 × 0.7 = maximum burnable area considered.

$$\text{Measurements } \frac{2 + 3 + 4}{3} = \text{area burned}$$

$$\frac{\text{Area burned}}{\text{Maximum burnable area}} \times 100 = \%\ \text{burn severity}$$



Specimen No.	EP47	Pressure (psia)	80	Substrate	Ti 3-8-6-4-4
Coating	Pt/Cu/Ni	Temperature (°F)	825		
Thickness (Mil)	2	Air Velocity (ft/sec)	800		

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Figure 8. Burn Severity Acquisition Data Points

High Speed Film Data

The majority of test data was obtained from the high-speed film coverage of each test run. This data took the form of:

1. Ignition time
2. Average chordwise burn velocity
3. Burn-through time.

Review and analyis of the high-speed film was performed using a Model 76 Data Analyzer, as shown in Figure 9. This system combines a film motion analyzer with sonic digitizer, TTY and minicomputer including interface and software program for computing line length, inside or outside angles and area. This special test equipment permitted achieving an improvement in the quality of combustion data extracted from the run films, as compared to previously employed techniques. In addition, its capability to provide rapid, direct readout and printout of distance, angles, and area measurements significantly decreased the time required to extract this data from the resulting large amount of test run film.

The Model 76 Film Data Analyzer hardware consists of the following:

1. NAC Film Motion Analyzer Model 160B

2. Graph pen sonic digitizer Model GP-3, electronically interfaced to the computer, and mechanically interfaced to the film analyzer

3. Data General NOVA 3 computer system including TTY.

The balance of this subsection contains a description of the typical data acquisition sequence used in extracting the primary test data from the film.

To determine specimen ignition time, the number of photographic frames between igniter ignition and specimen ignition were divided by the number of frames per second. Igniter ignition was considered to be the first visible change of the red (helium-neon) laser beam to yellow, indicating heating by the CO_2 laser beam. The specimen ignition was established as the first visible indication that the leading edge of the specimen was being consumed through sustained combustion (see Figure 10). Location of the leading edge was most readily identified from a frame containing sparks or flares of sufficient intensity to permit specimen definition.

Chordwise burn velocity was calculated by dividing the actual specimen width by the burn-through time. Burn-through time was calculated from the number of frames between specimen ignition and burn-through divided by the number of frames per second for the particular roll of film. A printed grid on transparent acetate film was overlaid on the Data Analyzer screen. This grid was used with the X and Y cursors to define the specimen boundaries. Burn-through time was recorded when the burn traveled across the width of the specimen (see Figure 11).

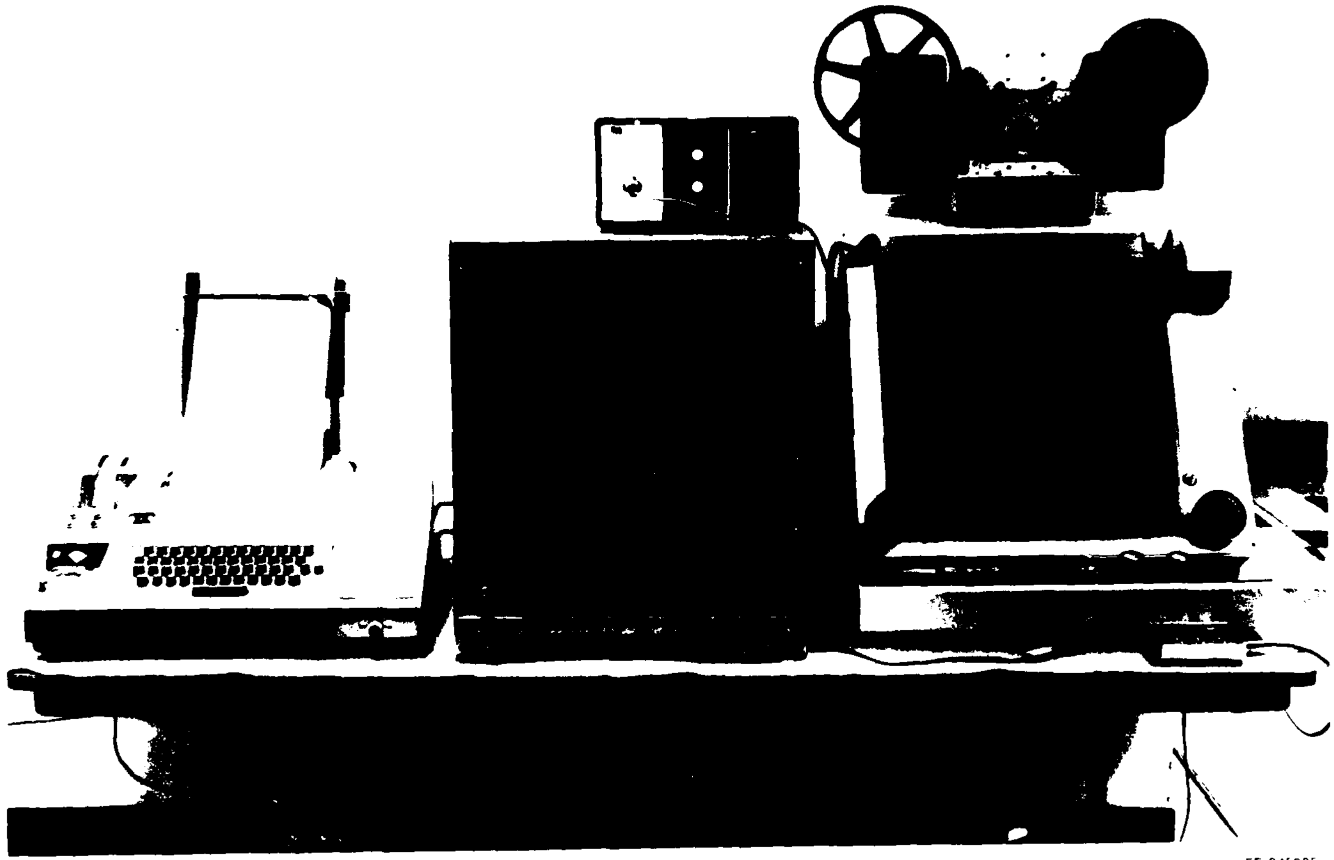

Figure 9. Model 76 NAC Film Motion Analyzer

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Figure 10. Determination of Specimen Ignition

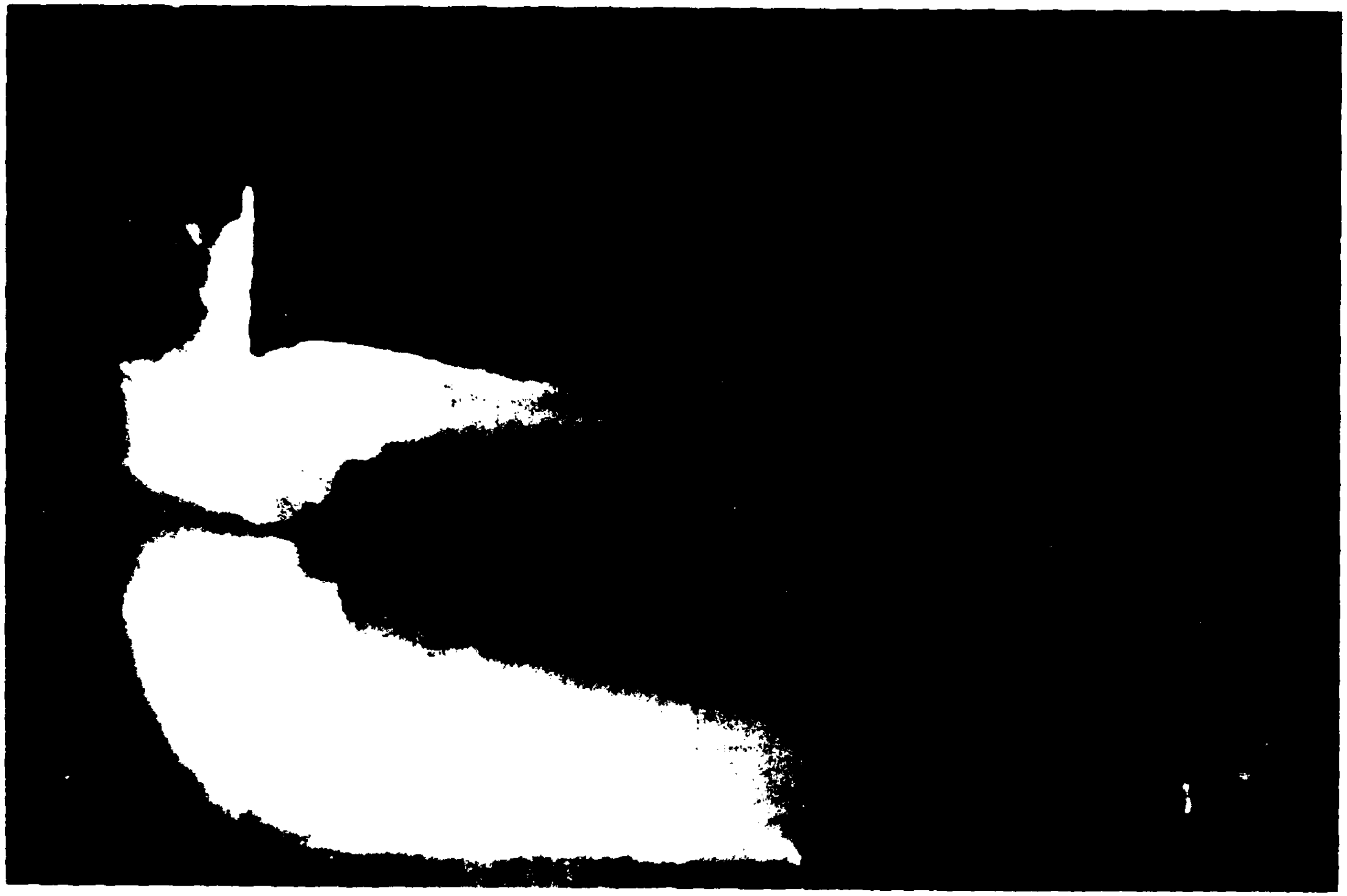

Figure [illegible]. Enlargement of Burn Through

DATA ACCURACY ASSESSMENT

Time Data Accuracy

Time data was used only in the calculation of chordwise burn velocity. The accuracy of this time data was dependent on two factors. First, and most significant, was the determination of test specimen ignition time. This was established as the first photographic frame containing evidence of specimen ignition as defined below. Since the identification of this frame involved individual judgment, a separate test was conducted to evaluate the influence of this judgment factor. Based on the results of using three persons evaluating 10 high-speed films, it was determined that the error in identifying specimen ignition did not exceed 10 frames (approximately 0.010 sec). Since the minimum determined burn-through time was approximately 0.4 sec, this ignition time error did not exceed 2.5%.

The second factor affecting ignition and combustion event timing is the true camera film transport rate. This rate was set on the camera indication of 1000 frames per sec. Because film transport rate tended to vary slightly from run to run, it was necessary to determine the actual time interval of an individual frame on the photographic record of each test run. This was accomplished by counting the number of Hz pulse generator annotations recorded on a 100-frame segment selected from the burn portion of the run film. From this actual time for the occurrence of 100 frames, the true frame rate can be readily calculated. The accuracy of this frame rate data is estimated to be 2 frames per sec, or approximately 0.2%.

Distance Data Accuracy

The accuracy of distance measurement data was dependent on judgment considerations as they influenced the location of a measurement point.

The absolute location of a point, as determined by the digitizer pen point, produced a discrete digital readout to 0.0025 mm (0.0001 in.). When divided by the magnification factor produced at the Data Analyzer screen (approximately 2.7 to 2.8), this resulted in an absolute location error of less than 0.001 mm (0.00004 in.). This is insignificant when compared to other measurement errors.

To quantitatively assess the reproducibility of a given distance measurement, a separate test was conducted. For this test the magnified width of a combustion specimen was repeatedly measured (24 times) at the Data Analyzer screen. Results showed that at a 95% confidence level the readings fell within a range of ±0.6% around the average.

Area Data Accuracy

Area data was required to permit calculation of burn severity, i.e., the percentage of burnable area of the original specimen which actually burned.

The accuracy of the burn severity data is influenced by the faithfulness of reconstructing the burned specimen fragments for photographing and subsequent area measurements. An analysis of the original length data of the specimens which burned indicated an average of 76.3 mm (3.005 in.) with a 95% confidence range of ±0.9 mm (0.036 in.). By restoring all burned specimens through the use of a 76.2 mm (3.000 in.) template, the maximum error introduced did not exceed 1.2% for 95% of the specimens.

The measurement of specimen total area, as performed on the Data Analyzer, consisted of setting the sonic digitizer pen point successively at the four corners of the specimen photograph. The accuracy of this determination thus becomes dependent on the precision with which these points can be identified. Since this technique is basically the same as for distance determinations, the accuracy is the same.

The determination of specimen burn area is performed on the reconstructed photograph by tracing the burned area with the sonic digitizer pen. The accuracy of this process, therefore, is determined by the skill of the individual doing the tracing. A separate test of 25 repetitive readings of a given burn area (approximately 50% burn severity) showed that a 95% confidence limit for the determined average was ± 0.7%. This assessment was conducted using the individual responsible for the determination of all burn severities.

Ignition Event Accuracy

Time to specimen ignition was originally planned as a parameter for evaluation in this program. However, lack of sufficient data correlation forced the elimination of ignition time as a significant test result. Since ignition time was not used in the data analysis, the accuracy of its determination was irrelevant.

Analysis of Data

The independant variables employed in the data analysis were test chamber pressure, temperature and airstream velocity, material type, coating thickness, chordwise burn velocity and burn severity. There were 291 observations with these variables collected and input into a sequential dataset for computer usage. The data was analyzed using the Statistical Analysis System (SAS). This system was chosen because it provides options for information storage and retrieval, data modification and programming and statistical analysis.

Ignition Time

The initial analysis of ignition time data failed to yield relationships having acceptable statistical correlation. An inspection of individual data points, however, shows the presence of trends particularly as this parameter is influenced by pressure. The statistical solution of test data indicates a large scatter.

Specimen ignition is dependent on environmental conditions of pressure and air velocity and the amount of heat supplied per unit area by the impinging molten metal. The amount of heat supplied to the specimen at any one time is determined by the size of the discrete particles of molten metal leaving the igniter. This particle size is dependent on the drag force exerted by the air flow (air velocity). The quantity of heat provided to effect ignition is determined through the random parameters of molten metal particle size and frequency of hit. Additionally, the randomness of the time of molten metal impingement is large enough to mask the effects produced by a coating as it differs from the baseline. Thus the ignition time data has a randomness incorporated in it that precludes the use as a criterion to evaluate the effects of coatings and alloys on titanium combustion.

Burn Severity

Burn severity values for each test specimen in the basic program matrix, as defined previously, are included in Appendices A, B and C and illustrated pictorially in Figures 12-A through 12-F. These values were subjected to a computerized stepwise regression analysis to identify which parameters were important in determining trends in the dependent variable, i.e., burn severity. Only parameters which were significant at a 90% confidence level were included in the development of the models. The parameters considered were substrate material, coating type, coating thickness, temperature, pressure, and airstream velocity.

Table 1 contains the generalized burn severity equations showing, for each substrate-coating system, the parameters exhibiting at least a 90% confidence level of influence. Corresponding to each equation Table 1 also shows the regression analysis data.

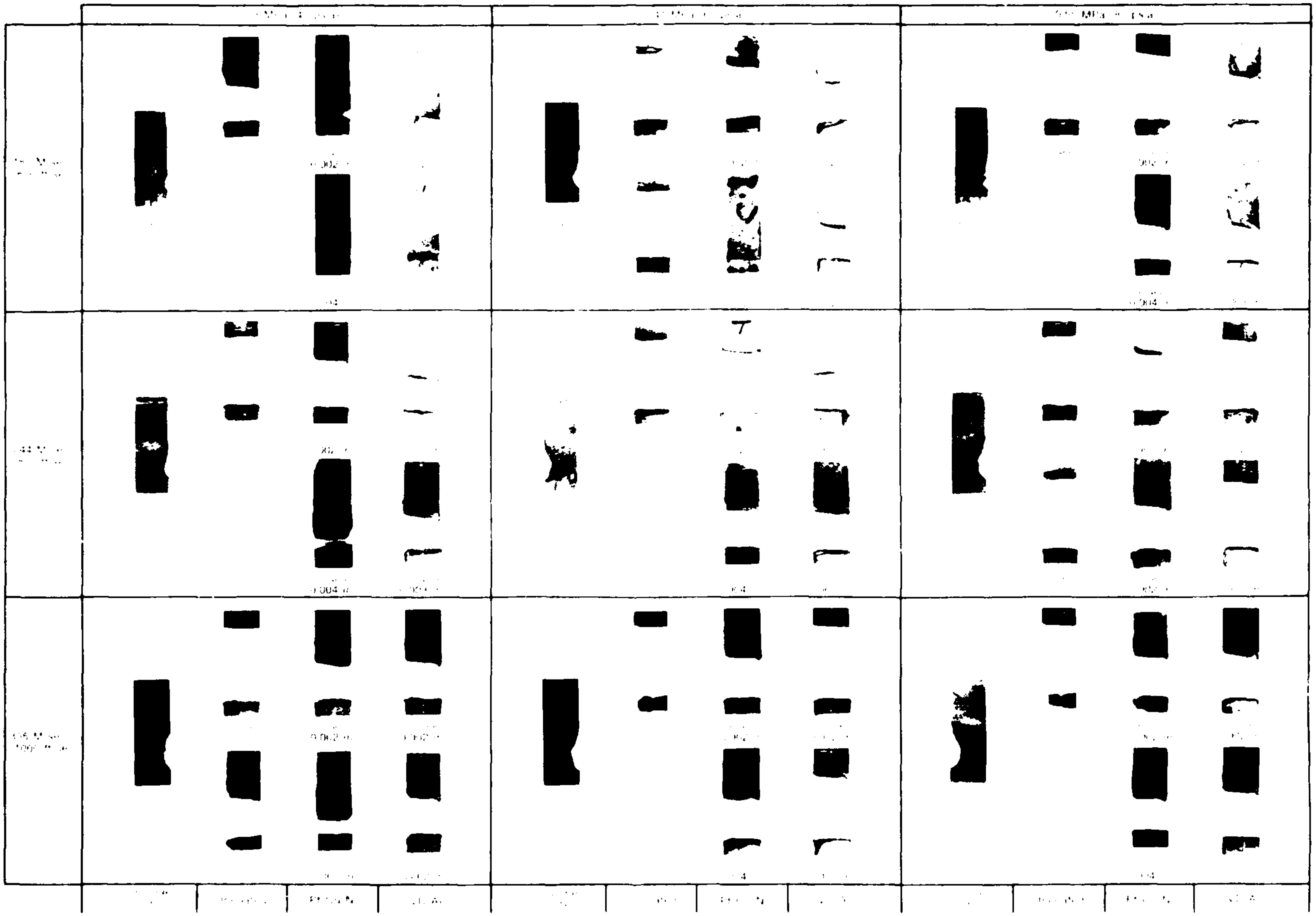

Figure 12A. Combustion Results at 316°C (600°F) Substrate: Ti 8Al-1Mo-1V

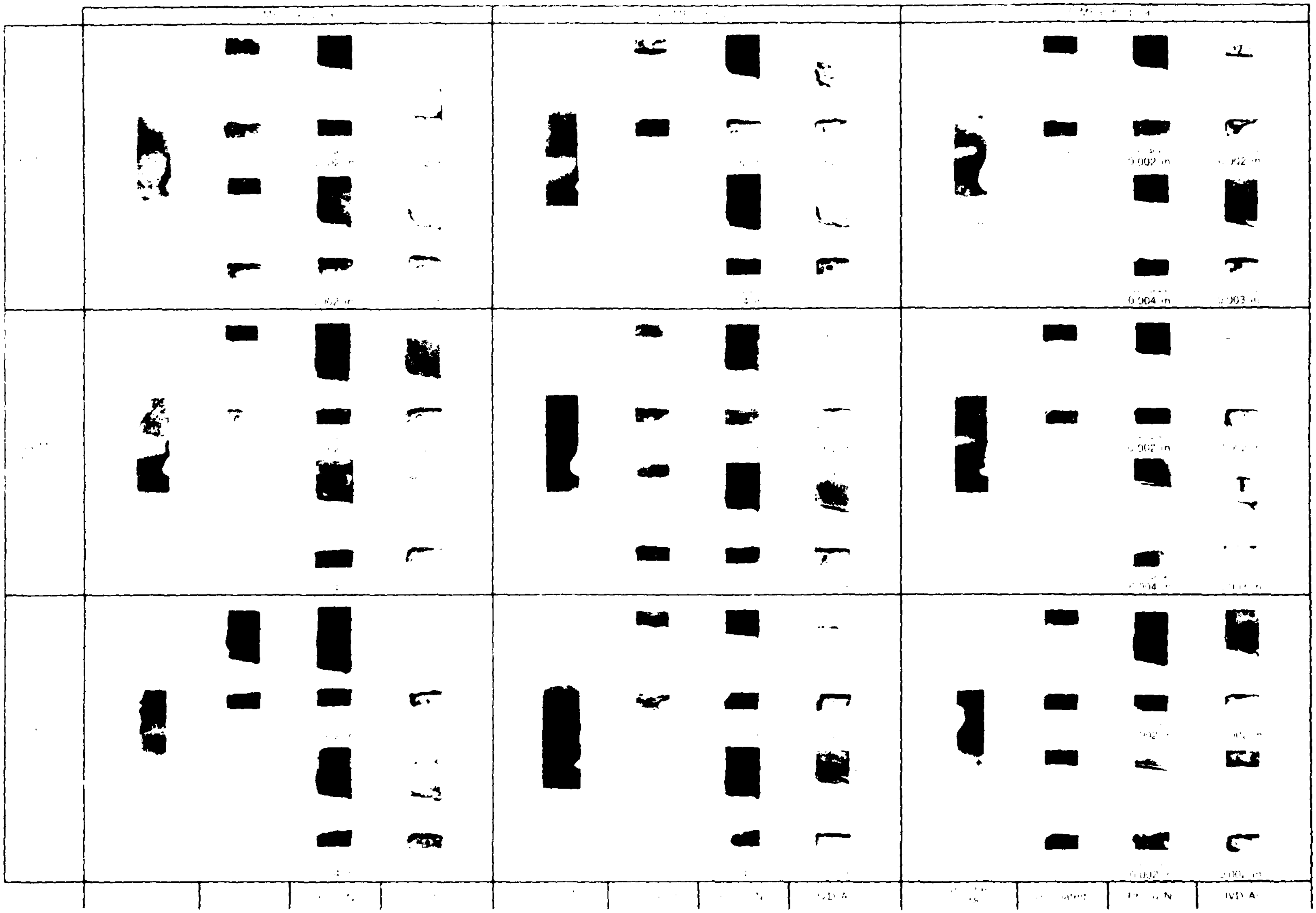

Figure 12B. Combustion Results at 385°C (725°F) Substrate: Ti 8Al-1Mo-1V

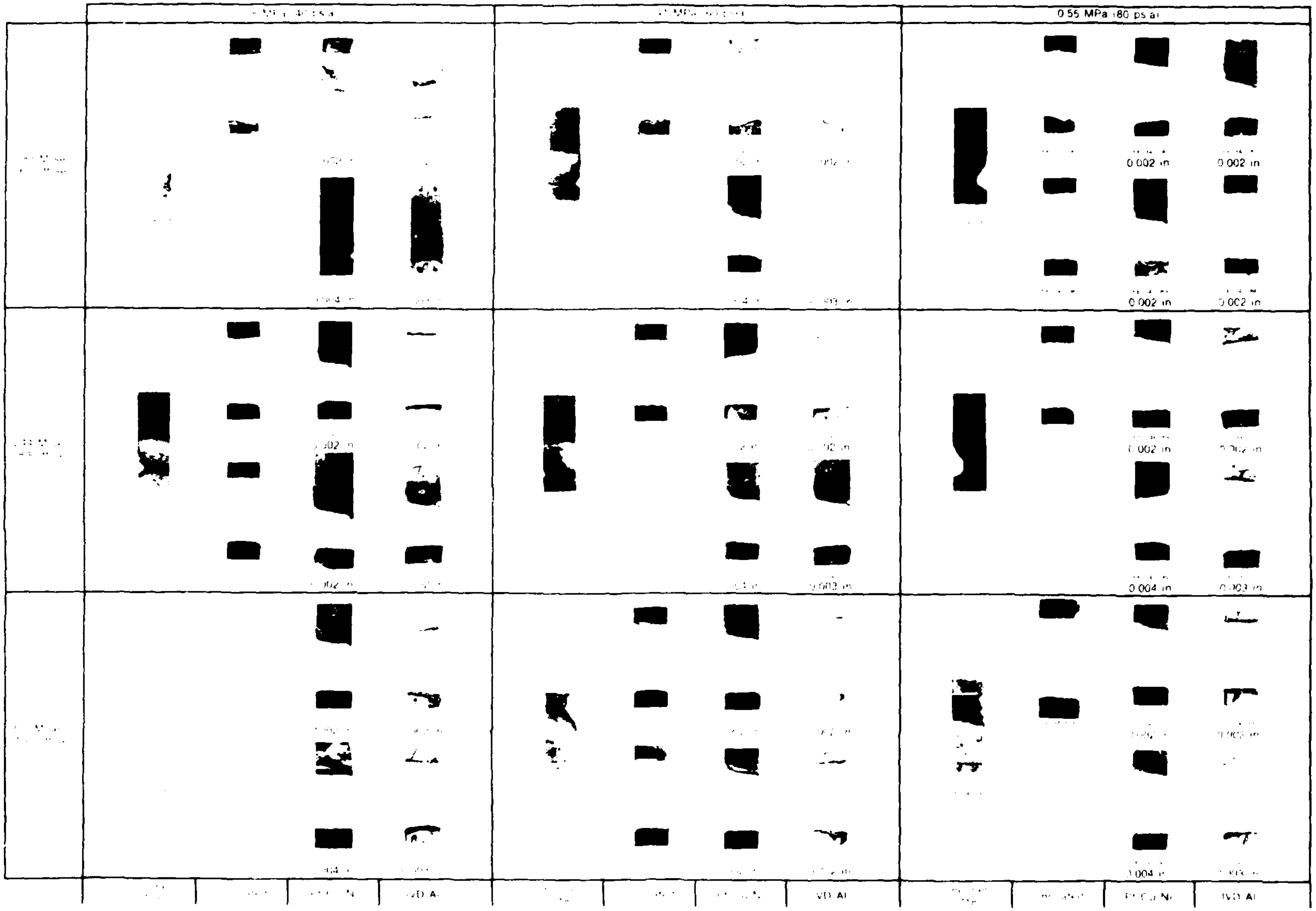

Figure 12C. Combustion Results at 441 C (825 F) Substrate: Ti 8Al 1Mo-1V

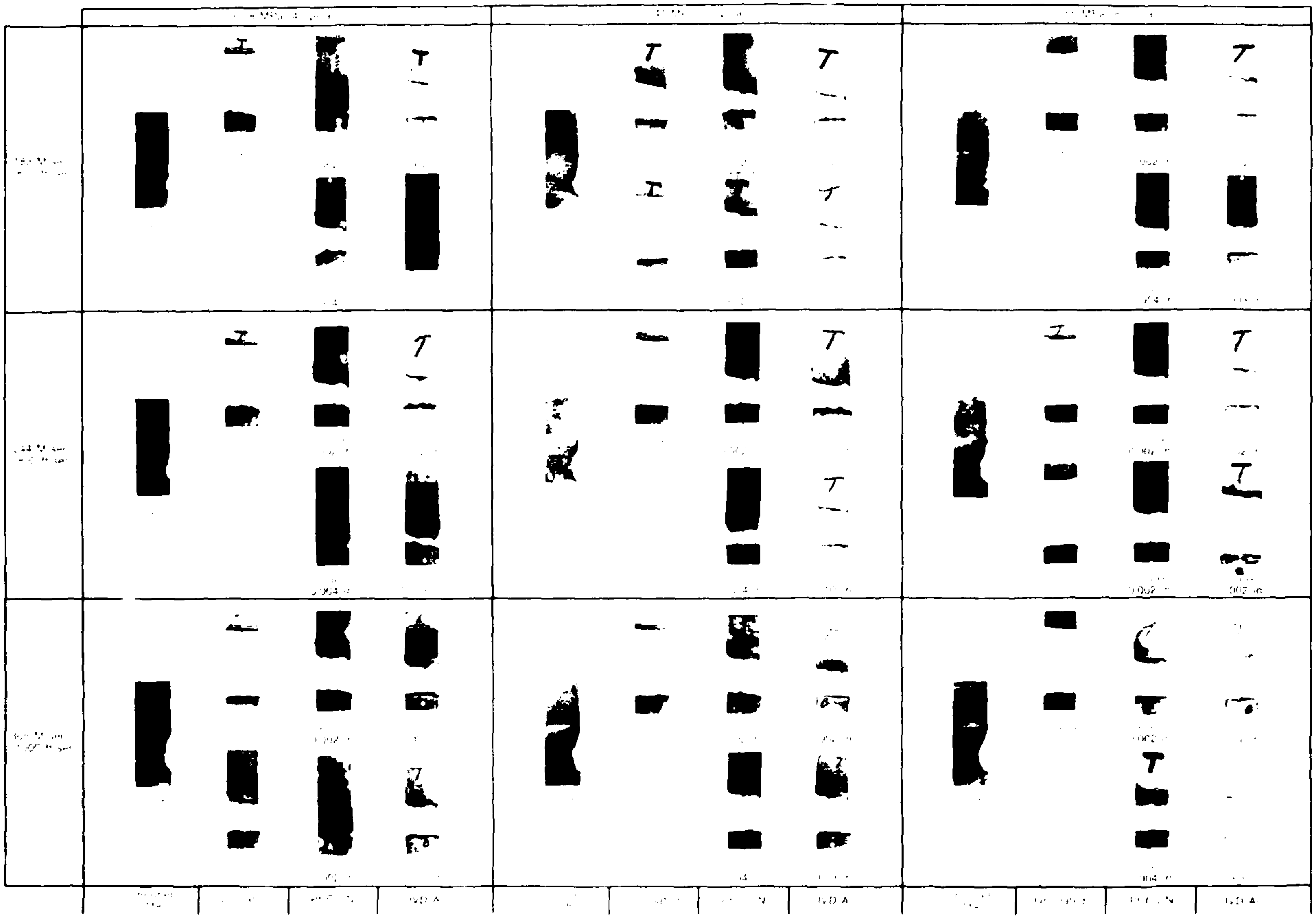

Figure 12D. Combustion Results at 316°C (600°F) Substrate: Ti 3Al-6CR-8V-0.4Mo-4Zr

Figure 12E. Combustion Results at 385°C (725°F) Substrate: Ti 3Al-6Cr-8V-0.4Mo-4Zr

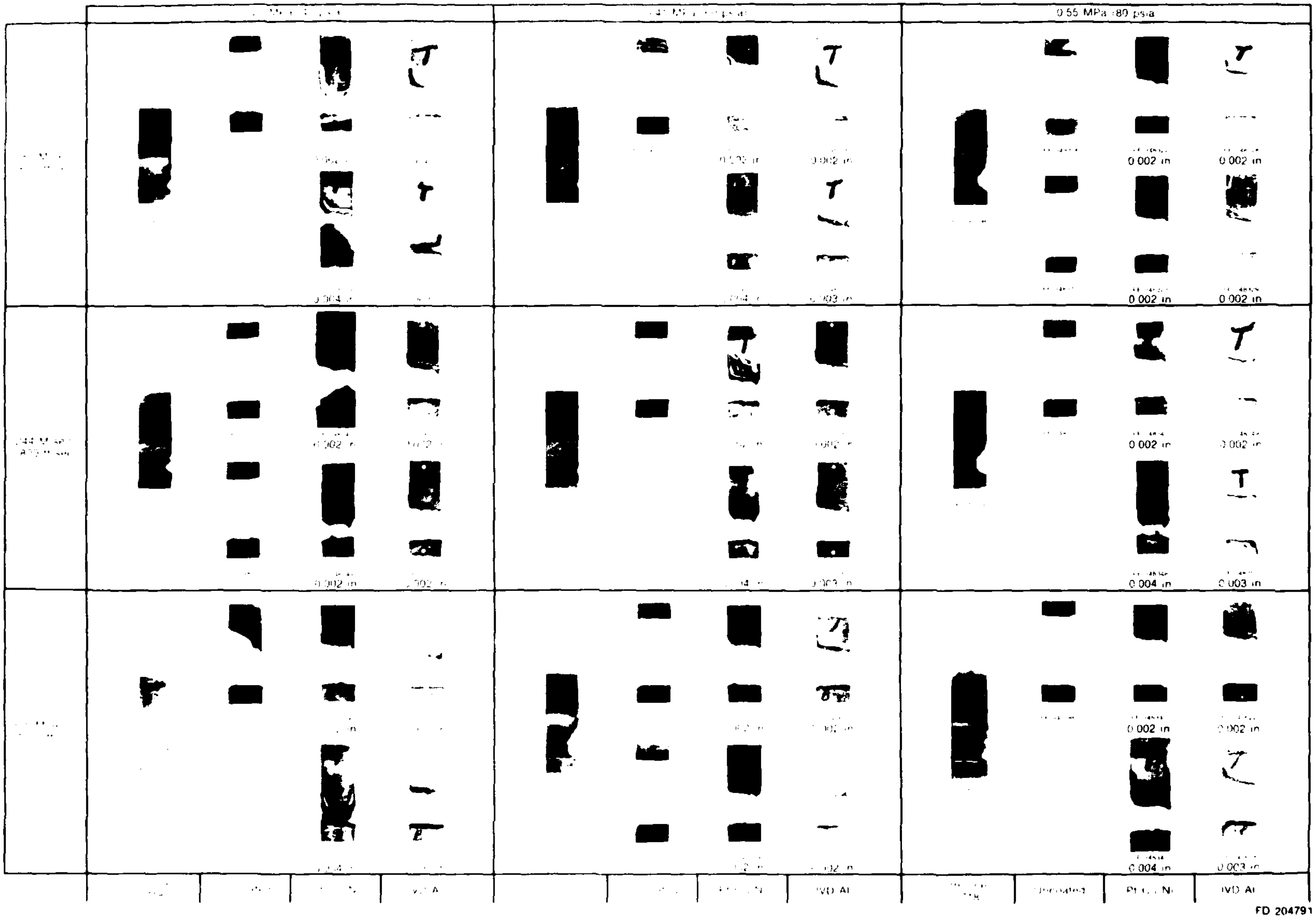

Figure 12F. Combustion Results at 441°C (825°F) Substrate: Ti 3Al-6Cr-8V-0.4Mo-4Zr

As shown by the R squared value listed in the "Regression Analysis Data" column, the correlation coefficients for the "best fit" equations are very low (0.41 to 0.67). This dictates that extreme caution must be exercised when using the mathematical data for predicting individual cases of burn severity.

For Ti 3-6-8-4-4 substrate, Table 1 shows that the equation for burn severity due to the IVD aluminum contains no coating thickness parameter. Thus, although the presence of the IVD aluminum did reduce burn severity, its thickness, within the range tested, could not be shown to be significant in reducing the magnitude of burn. Therefore, for alloy Ti 3-6-8-4-4 the severity of combustion is better controlled by the Pt/Cu/Ni coating.

The presence of trends, however, is quite apparent when studying Figure 12. The horizontal comparison of a given coating on a given page illustrates the increase of burn severity with increase of pressure. Similarly, columnar comparisons substantiate the fact that the equations show a slightly significant effect due to airstream velocity. The visual lack of a temperature effect is not as readily discernible because of the need for a page-to-page comparison of burn severities.

With respect to the performance of the additional test specimens, burn severity (shown in Appendix C) did not conform to the trends of the general equations of Table 1. Following is a comparison of the Cu/Al additional test specimens with the solution obtained by using the equation for the Pt/Cu/Ni coating:

		Burn Severity, %	
Coating System		*Reconstructed Photo*	*Predicted by Equation**
Cu/Al (0.002)			
Where:	Cu = 0.002	36.3	45.5
	Cu = 0.0043	39.8	35.2
	Cu = 0.0055	35.5	29.8
	Cu = 0.008	29.3	18.6

*Based upon system consisting of:

Pt (1 micron)/Cu/Ni (0.0003 in.)

Although this comparison is not strictly valid, it does appear to show that the aluminum overcoat has the effect of decreasing the effect of copper while simultaneously masking the effect of its thickness.

Performance of the Ni/Al coating (shown in Appendix C) establishes a strong correlation of increased burn severity with increased nickel thickness. Since the nickel would be expected to form a lower melting titanium alloy during combustion, there again appears to be evidence to support a conclusion that the presence of the aluminum overcoat has favored the sustained propagation of titanium combustion.

One possible explaination for this performance is that the lower-melting aluminum overcoat has properties of viscosity and surface tension which would tend to increase the melt area during combustion. As has been observed in previous work (References 3 and 4), an increase in melt area generally results in an increase in the severity of burn.

As was experienced in previous testing (Reference 5), the Ti Al specimens could not be ignited at successively increasing pressures (Appendix C).

TABLE 1. BURN SEVERITY EQUATIONS

Coating System	*Generalized Equation*	*Regression Analysis Data*					
Uncoated Ti 8-1-1	$B=K+aP+bT-cT^2$			R Square = 0.41172324			
			DF	Sum of Squares	Mean Square	F	Prob>F
		Regression	3	3021.32702093	1007.10900698	7.47	0.0006
		Error	32	4316.92047907	134.90376497		
		Total	35	7338.24750000			
			B Value	Std Error	Type II SS	F	Prob>F
		Intercept	−458.90520596				
		Pres	0.31231985	0.11854446	936.39838847	6.94	0.0129
		Temp	1.55251815	0.47157252	1462.17875125	10.84	0.0024
		Temp2	−0.00112219	0.00033142	1546.67231258	11.47	0.0019
Pt/Cu/Ni on Ti 8-1-1	$B=K-aC+bP+cT-dT^2+eV^2$			R Square = 0.53346949			
			DF	Sum of Squares	Mean Square	F	Prob>F
		Regression	5	16013.34583195	3202.66916639	10.29	0.0001
		Error	45	14004.01456021	311.20032356		
		Total	50	30017.36039216			
			B Value	Std Error	Type II SS	F	Prob>F
		Intercept	−544.25803397				
		Thick	−4119.91149419	2397.34896356	919.07997054	2.95	0.0926
		Pres	0.86708585	0.15491519	9749.36224823	31.33	0.0001
		Temp	1.46460948	0.59229016	1902.89438724	6.11	0.0172
		Temp2	−0.00098627	0.00041688	1741.89007322	5.60	0.0224
		Vel2	0.00003796	0.00001322	2566.60069190	8.25	0.0062
IVD Al on Ti 8-1-1	$B=K-aC+bP+cT^2+dV-eV^2$			R Square = 0.66963864			
			DF	Sum of Squares	Mean Square	F	Prob>F
		Regression	5	25882.82789443	5176.56557889	19.46	0.0001
		Error	48	12769.10543890	266.02302998		
		Total	53	38651.93333333			
			B Value	Std Error	Type II SS	F	Prob>F
		Intercept	405.79300697				
		Thick	8829.28547946	4729.89014807	926.97547770	3.48	0.0681
		Pres	0.58069895	0.13621459	4834.75072586	18.17	0.0001
		Temp2	0.00004993	0.00001765	2128.33689891	8.00	0.0068
		Vel	0.99077736	0.22122221	5335.97665675	20.06	0.0001
		Vel2	0.00055455	0.00013915	4225.10527385	15.88	0.0002

TABLE 1. BURN SEVERITY EQUATIONS (Continued)

Coating System	Generalized Equation	Regression Analysis Data					
Uncoated Ti 3-6-8-4-4	$B=K+aP+bT+cV-dV^2$			R Square = 0.46477424			
			DF	Sum of Squares	Mean Square	F	Prob > F
		Regression	4	3615.90981948	903.97745487	6.51	0.0007
		Error	30	4164.01760909	138.80058697		
		Total	34	7779.92742857			
			B Value	Std Error	Type II SS	F	Prob > F
		Intercept	112.20136758				
		Pres	0.22548467	0.12358610	462.04695956	3.33	0.0780
		Temp	0.04124740	0.02201552	487.22140946	3.51	0.0708
		Vel	0.46148921	0.21145661	661.10719117	4.76	0.0370
		Vel2	-0.00033280	0.00013663	823.57892985	5.93	0.0210
Pt/Cu/Ni on Ti 3-6-8-4-4	$B=K+aC^2+bP+cP^2+dT$			R Square = 0.55928193			
			DF	Sum of Squares	Mean Square	F	Prob > F
		Regression	4	11982.35418295	2995.58854574	15.23	0.0001
		Error	48	9442.17902460	196.71206301		
		Total	52	21424.53320755			
			B Value	Std Error	Type II SS	F	Prob > F
		Intercept	135.22409991				
		Thick2	914081.72295238	333697.61746440	1476.02880163	7.50	0.0086
		Pres	4.38849654	1.22999370	2504.12925676	12.73	0.0008
		Pres2	0.03038331	0.01018244	1751.44964474	8.90	0.0045
		Temp	0.04421735	0.02104620	868.29808622	4.41	0.0409

TABLE 1. BURN SEVERITY EQUATIONS (Continued)

Coating System	*Generalized Equation*	*Regression Analysis Data*					
IVD Al on Ti 3-6-8-4-4	$B = K + aP + bT$			R Square	0.43467459		
			DF	Sum of Squares	Mean Square	F	Prob > F
		Regression	2	2928.74756982	1464.37378491	19.61	0.0001
		Error	51	3809.04576351	74.68717183		
		Total	53	6737.79333333			
			B Value	Std Error	Type II SS	F	Prob > F
		Intercept	2.63274309				
		Pres	0.43841366	0.07234824	2742.57357327	36.72	0.0001
		Temp	0.02730381	0.01311117	323.89869009	4.34	0.0423

where: B = Burn severity, %
C = Coating thickness, in.
P = Pressure, psia
T = Temperature, °F
V = Air velocity, ft/sec.

Chordwise Burn Velocity

Upon regression analysis, the CBV data for all specimens applied over the Ti 8-1-1 substrate did not establish a significant coating type influence. Thus the Ti 8-1-1 equation shown in Table 2 represents a pooling of data for the uncoated substrate and the two coating systems. In this relationship, as pressure and/or airstream velocity increase, chordwise burn velocity increases. A straightforward explanation exists for this relationship. As pressure increases, the amount of oxidizer available for reaction increases, which in turn increases the reaction rate (chordwise burn velocity). The effect of airstream velocity is in the same direction as the pressure parameter, but to a lesser extent. Airstream velocity affects the rate at which the molten substrate material "wets" the specimen surface, i.e., moves across the specimen surface. An increase in the rate of molten metal propagation results in an increase in the rate of heat transfer, which in turn results in an increase in combustion rate and, thus, chordwise burn velocity.

Airstream temperature affects chordwise burn velocity in the same direction as pressure and airstream velocity. An increase in airstream temperature increases substrate temperature, thereby decreasing the temperature gradient between the molten material and the substrate. All things considered, such as decreased heat transfer rate, the lower the temperature gradient the higher will be the rate of molten metal propagation. An increase in this propagation corresponds to an increase in chordwise burn velocity.

While the type of coating was not significant, the thickness of an applied coating did affect chordwise burn velocity. From the Ti 8-1-1 equation, an increase in coating thickness results in a decrease in chordwise burn velocity. A reasonable mechanism for this is that the moving molten substrate material melts the coating before the substrate is heated sufficiently to propagate combustion. Because the melted coating exhibits different viscosity and surface tension characteristics than the propagating molten titanium, the difference could cause the molten substrate and coating to become entrained in the airstream more readily instead of propagating further across the specimen surface. The loss of molten material to the airstream results in a decrease in chordwise burn velocity.

Analysis of the two coating systems performance when applied to the Ti 3-6-8-4-4 substrate established that both the Pt/Cu/Ni, and Al coatings reduced the CBV over that of the uncoated base material. In addition, the Pt/Cu/Ni coating was shown to have a significantly lower mean burn rate than the aluminum. The overall influence of each independent variable proved to be in the same general direction as the Ti 8-1-1 specimens.

Direct comparison of CBV for the Ti 8Al-1Mo-1V and Ti 3Al-6Cr-8V-0.4Mo-4Zr specimens cannot be made due to the difference in the specimen thickness.

In a past program (Reference 4) involving laser ignition a significant relationship was derived between CBV and specimen thickness. However, attempts to correlate CBV values reported herein with results from the previous program are precluded because of alloy differences (the previous program did not include Ti 3-6-8-4-4) and differences in the source of ignition (molten metal vs laser).

In general, the CBV values resulting from molten metal ignition were higher than the CBV values from laser ignition. A possible explanation is that the molten metal ignition generates more melt area than the laser ignition. This melt area is the specimen area covered by molten metal that initiates combustion at the leading edge of the specimen. In the past when using laser ignition, it was determined that the greater the melt area formed the greater the CBV. Thus, the higher CBV values from molten metal ignition indicated that a larger initial melt area was formed than was previously experienced with laser ignition.

TABLE 2. CHORDWISE BURN VELOCITY EQUATIONS

Coating System	*Generalized Equation*	*Regression Analysis Data*					
Ti 8-1-1 Pt/Cu/Ni on Ti 8-1-1 IVD Al on Ti 8-1-1	$CBV = K + aC + bP + cT^2 + dV + eV^2$			R Square 0.91474095			
			DF	Sum of Squares	Mean Square	F	Prob>F
		Regression	5	35.28097763	7.05619553	283.24	0.0001
		Error	132	3.28838747	0.02491203		
		Total	137	38.56936510			
			B Value	Std Error	Type II SS	F	Prob>F
		Intercept	3.53801606				
		Thick	55.11475508	10.39440056	0.70039965	28.11	0.0001
		Pres	0.02683346	0.00082011	26.66989246	1070.56	0.0001
		Vel	0.00574012	0.00122691	0.54528902	21.89	0.0001
		Vel2	-0.00000260	0.00000078	0.27968415	11.23	0.0011
		Temp2	0.00025104	0.00007706	0.26440686	10.61	0.0014
Ti 3-6-8-4-4 (Baseline)	$CBV = K + aP + bT + cV^2$			R Square = 0.89774781			
			DF	Sum of Squares	Mean Square	F	Prob>F
		Regression	3	11.62278744	3.87426248	90.72	0.0001
		Error	31	1.32381884	0.04270383		
		Total	34	12.94660629			
			B Value	Std Error	Type II SS	F	Prob>F
		Intercept	2.00855279				
		Pres	0.03080425	0.00215866	8.69597050	203.63	0.0001
		Temp	0.00144136	0.00038286	0.60525518	14.17	0.0007
		Vel2	0.00000106	0.00000016	1.81341428	42.46	0.0001
Pt/Cu/Ni on Ti 3-6-8-4-4	$CBV = K + aC^2 + bP + cV^2$			R Square = 0.79695053			
			DF	Sum of Squares	Mean Square	F	Prob>F
		Regression	3	17.14126109	5.71375370	60.18	0.0001
		Error	46	4.36730253	0.09494136		
		Total	49	21.50856362			
			B Value	Std Error	Type II SS	F	Prob>F
		Intercept	1.47358685				
		Thick2	15226.60882016	7994.54052152	0.34440925	3.63	0.0631
		Pres	0.03283339	0.00270777	13.95929792	147.03	0.0001
		Vel2	0.00000107	0.00000025	1.70072213	17.91	0.0001

TABLE 2. CHORDWISE BURN VELOCITY EQUATIONS (Continued)

Coating System	*Generalized Equation*	*Regression Analysis Data*					
IVD Al on Ti 3-6-8-4-4	$CBV=K-aC+bP+cT-dV+eV^2$			R Square = 0.88117097			
			DF	Sum of Squares	Mean Square	F	Prob > F
		Regression	5	12.57652598	2.51530520	66.74	0.0001
		Error	45	1.69598919	0.03768865		
		Total	50	14.27251518			
			B Value	Std Error	Type II SS	F	Prob > F
		Intercept	1.01335622				
		Thick	-145.32182163	58.72539096	0.23079181	6.12	0.0172
		Pres	0.02619701	0.00166759	9.30111910	246.79	0.0001
		Temp	0.00135145	0.00029533	0.78918886	20.94	0.0001
		Vel	-0.00720808	0.00335159	0.17432002	4.63	0.0369
		Vel2	0.00000583	0.00000223	0.25805977	6.85	0.0120

where: CBV = Chordwise burn velocity, in./sec
C = Coating thickness, in.
P = Pressure, psia
T = Temperature, °F
V = Air velocity, ft/sec.

It would appear that during the additional testing the two coating systems involving Cu/Al and Ni/Al create their own unique combustion characteristics and thus cannot be expected to follow even the trends of those systems studied in the basic program matrix.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSION

As a result of the extensive statistically designed testing performed during this program, certain general observations can be presented along with specific conclusions or trends as related to titanium combustion characteristics.

GENERAL OBSERVATIONS

The test technique employed, i.e., specimen ignition as a result of molten metal impingement, produces an externally high degree of environment severity. The test specimen is exposed to an erosive bombardment of burning titanium particles which, depending on size and transit time in the airstream, will attain temperatures of 1927°C (3500°F) to 2482°C (4500°F). Considering particle temperature alone, with an extended exposure to this environment, a successful coating must be a material of sufficient thickness and melting temperature above 2482°C (4500°F). When adding to this requirement the unknown influence of erosion, it becomes evident that existing economically and technically suitable materials may not even be available.

However, considering real life conditions surrounding the onset of titanium combustion in a gas turbine engine, the exposure quantity and time factors would tend to be minimal, thereby favoring the potential success of a less temperature/erosion resistant coating.

As detailed in the conclusions and trends discussed below, the rate of propagation and severity of burn can be minimized through the use of coatings even when the severe environment of the P&WA cascade test rig is employed.

IGNITION TIME

The large scatter of ignition time data yielded very low correlation coefficients for equations expressing the influence of the independent variables on this characteristic. This scatter is understandable when one considers:

1. The subjectivity of the identification of the ignition event, and

2. The inherent random nature of the molten particles striking the approximate 1.5 mm (0.060 in.) thick specimen leading edge.

Although it appears evident that the time to effect ignition, or the very onset of ignition itself, is dependent on the quantity of molten material striking the specimen, the test rig and procedure employed did not permit establishing this relationship.

BURN SEVERITY

Burn severity data also exhibited large scatter which was, however, not as severe as the ignition time data. Burn severity equations with correlation coefficients ranging from 0.41 to 0.67, although not considered as having established good statistical correlation, did permit the following observations and conclusions:

1. Test chamber air pressure was known to be the most significant variable. In all cases, an increase in pressure produced an increase in burn severity.

2. The presence of a coating on the specimen resulted in a decrease in burn severity.

3. As coating thickness increased, the burn severity decreased.

CHORDWISE BURN VELOCITY (CBV)

Equations for the expression of CBV consistently produced significantly high correlation coefficients of 0.80 to 0.91. Based on the analysis of these equations, the following conclusions can be reached:

1. An increase in pressure results in an increase in CBV.

2. An increase in velocity results in an increase in CBV.

3. Temperature effect on CBV appears to be very minor or negligible.

4. The presence of a coating decreased CBV.

5. As coating thickness increased, CBV decreased.

6. On a Ti 8-1-1 substrate the type of coating was not significant in controlling CBV.

7. On a Ti 3-6-8-4-4 substrate the Pt/Cu/Ni coating was shown to have a significantly lower mean CBV than the IVD Al.

Summary Conclusion

In summary consideration of all the above individual conclusions the IVD aluminum coating provided the maximum combustion protection for the Ti 8-1-1 substrate. Even though at the severe conditions tested this coating did not prevent substrate combustion, there are strong indications that under conditions of typical engine ignition initiation the presence of an IVD coating would either prevent ignition or prevent sustained combustion propagation.

Although Ti 3-6-8-4-4 is not known to be used in current gas turbine engines, for applications which could employ this alloy, the Pt/Cu/Ni coating would provide the better protection.

Recommendations

As a result of the experimental work performed under this program, the following recommendations are submitted to guide future work in the area of titanium alloy ignition and combustion:

1. A test program should be initiated to provide full-scale verification (via engine testing) of the capability of the IVD aluminum to perform as indicated during this program.

2. An alloy screening effort should be conducted in which alloying elements (known to retard combustion) are added to titanium in varying amounts. This program would include mechanical property characterization in addition to ignition and combustion tests.

3. Physical properties such as melting point, oxide solubility, heat of combustion, thermal conductivity and diffusivity, viscosity of the melt and surface tension (wetability) of melt on solid significantly influence the ignition and sustained combustion properties of titanium alloys. Data on these physical properties, however, is generally not available. A comprehensive effort is required to determine these properties, particularly for nonburning alloys, to serve as a guide to the formulation of new nonburning alloys having acceptable mechanical properties.

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APPENDIX A. COMBUSTION DATA FOR SUBSTRATE: Ti 3Al-6Cr-8V-0.4Mo-4Zr

Specimen No.	*Coating Type*	*Coating Thickness (in./mm)*	*Chamber Pressure (psia/MPa)*	*Chamber Temperature (°F/°C)*	*Air Velocity (ft/sec/m/sec)*	*Burn Severity (%)*	*Chordwise Burn Velocity (in./sec/cm/sec)*	*Ignition Time (sec)*
Environmental Condition No. 1								
AB-25	Baseline	N/A	40/0.28	597/314	586/179	86.4	0.711/1.81	3.839
EP-53	Pt/Cu/Ni	0.002/0.05	40/0.28	603/317	586/179	<1.0	N/A	N/A
EP-24	Pt/Cu/Ni	0.004/0.10	40/0.28	602/317	580/177	<1.0	N/A	N/A
EF-28	Aluminum	0.002/0.05	40/0.28	601/316	567/173	48.3	0.527/1.34	3.321
EF-78	Aluminum	0.003/0.07	40/0.28	598/314	566/173	34.7	0.497/1.26	3.339
Environmental Condition No. 2								
AB-26	Baseline	N/A	60/0.42	600/316	569/173	48.9	1.229/3.12	0.929
AB-27	Baseline	N/A	60/0.42	603/317	589/180	91.4	1.147/2.91	0.959
EP-54	Pt/Cu/Ni	0.002/0.05	60/0.42	599/315	573/175	52.3	0.926/2.35	1.814
EP-55	Pt/Cu/Ni	0.002/0.05	60/0.42	601/316	574/175	25.3	0.999/2.54	2.785
EF-26	Aluminum	0.002/0.05	60/0.42	600/316	574/175	32.1	1.056/2.68	2.584
EF-27	Aluminum	0.002/0.05	60/0.42	600/316	574/175	43.7	0.996/2.53	1.186
Environmental Condition No. 3								
AB-28	Baseline	N/A	80/0.56	602/316	571/174	90.5	1.498/3.80	0.813
EP-56	Pt/Cu/Ni	0.002/0.05	80/0.56	601/316	580/177	52.3	1.247/3.17	0.899
EP-25	Pt/Cu/Ni	0.004/0.10	80/0.56	600/316	570/174	35.0	1.005/2.55	1.123
EF-29	Aluminum	0.002/0.05	80/0.56	602/317	571/174	49.1	1.211/3.08	0.201
EF-79	Aluminum	0.003/0.08	80/0.56	601/3.16	581/177	39.1	1.072/2.72	0.7873
Environmental Condition No. 4								
AB-29	Baseline	N/A	40/0.28	725/385	604/184	91.0	0.706/1.79	2.476
AB-30	Baseline	N/A	40/0.28	724/384	606/185	88.6	0.912/2.32	3.724
EP-63	Pt/Cu/Ni	0.002/0.05	40/0.28	724/384	600/183	28.0	0.666/1.69	4.779
EP-64	Pt/Cu/Ni	0.002/0.05	40/0.28	726/385	600/183	<1.0	N/A	N/A
EF-30	Aluminum	0.002/0.05	40/0.28	726/385	600/183	23.7	0.765/1.94	3.134
EF-31	Aluminum	0.002/0.05	40/0.28	727/386	600/183	37.6	0.494/1.25	2.604
Environmental Condition No. 5								
AB-31	Baseline	N/A	60/0.42	725/385	607/185	90.2	1.217/3.09	0.964
EP-65	Pt/Cu/Ni	0.002/0.05	60/0.42	725/385	607/185	51.1	0.847/2.15	1.432
EP-26	Pt/Cu/Ni	0.004/0.10	60/0.42	726/385	608/185	68.0	0.814/2.07	1.760
EF-32	Aluminum	0.002/0.05	60/0.42	725/385	597/182	52.0	1.131/2.87	1.170
EF-80	Aluminum	0.003/0.08	60/0.42	724/384	597/182	38.0	0.854/2.17	0.979
Environmental Condition No. 6								
AB-32	Baseline	N/A	80/0.56	723/384	614/187	92.9	1.690/4.29	0.950
EP-66	Pt/Cu/Ni	0.002/0.05	80/0.56	727/386	604/184	55.7	1.225/3.11	0.752
EP-27	Pt/Cu/Ni	0.004/0.10	80/0.56	724/384	604/184	43.2	1.024/2.60	0.838
EF-33	Aluminum	0.002/0.05	80/0.56	728/387	604/184	57.0	1.483/3.77	0.752
EF-81	Aluminum	0.003/0.08	80/0.56	723/384	605/184	58.2	1.451/3.69	0.749

APPENDIX A. COMBUSTION DATA FOR SUBSTRATE: Ti 3Al-6Cr-8V-0.4Mo-4Zr (Continued)

Specimen No.	Coating Type	Coating Thickness (in./mm)	Chamber Pressure (psia/MPa)	Chamber Temperature (°F/°C)	Air Velocity (ft/sec/m/sec)	Burn Severity (%)	Chordwise Burn Velocity (in./sec/cm/sec)	Ignition Time (sec)
Environmental Condition No. 7								
AB-34	Baseline	N/A	40/0.28	825/441	612/187	89.8	0.874/2.22	*
EP-67	Pt/Cu/Ni	0.002/0.05	40/0.28	826/441	613/187	24.9	0.581/1.48	1.042
EP-28	Pt/Cu/Ni	0.004/0.10	40/0.28	825/441	635/194	22.7	**	**
EF-34	Aluminum	0.002/0.05	40/0.28	822/439	618/188	38.1	0.595/1.51	3.499
EF-82	Aluminum	0.003/0.08	40/0.28	823/439	634/193	1.9	N/A	N/A
Environmental Condition No. 8								
AB-35	Baseline	N/A	60/0.42	823/439	609/186	95.4	1.361/3.46	0.622
EP-68	Pt/Cu/Ni	0.002/0.05	60/0.42	824/440	643/196	68.3	0.873/2.22	1.612
EP-29	Pt/Cu/Ni	0.004/0.10	60/0.42	824/440	640/195	51.9	0.962/2.44	0.935
EF-35	Aluminum	0.002/0.05	60/0.42	825/441	628/191	43.2	1.133/2.88	1.277
EF-83	Aluminum	0.003/0.08	60/0.42	828/442	639/195	45.6	1.057/2.68	0.953
Environmental Condition No. 9								
AB-33	Baseline	N/A	80/0.56	824/440	643/196	93.0	1.959/4.98	0.550
AB-36	Baseline	N/A	80/0.56	827/442	645/197	95.8	1.884/4.79	0.804
EP-69	Pt/Cu/Ni	0.002/0.05	80/0.56	824/440	644/196	50.6	1.762/4.48	0.781
EP-70	Pt/Cu/Ni	0.002/0.05	80/0.56	826/441	646/197	53.2	1.605/4.08	0.789
EF-36	Aluminum	0.002/0.05	80/0.56	822/439	650/198	60.7	1.749/4.44	0.584
EF-37	Aluminum	0.002/0.05	80/0.56	825/441	633/193	47.5	1.392/3.54	0.591
Environmental Condition No. 10								
AB-13	Baseline	N/A	40/0.28	599/315	726/221	86.5	0.849/2.16	3.604
EP-1	Pt/Cu/Ni	0.002/0.05	40/0.28	599/315	739/225	29.7	0.554/1.41	3.273
EP-16	Pt/Cu/Ni	0.004/0.10	40/0.28	601/316	774/236	< 1.0	N/A	N/A
EF-13	Aluminum	0.002/0.05	40/0.28	598/314	741/226	34.5	0.635/1.61	3.942
EF-70	Aluminum	0.003/0.08	40/0.28	599/315	741/226	9.6	0.363/0.92	2.788
Environmental Condition No. 11								
AB-14	Baseline	N/A	60/0.42	599/315	770/235	91.5	1.287/3.27	0.800
EP-2	Pt/Cu/Ni	0.002/0.05	60/0.42	599/315	744/227	35.9	0.923/2.34	1.318
EP-15	Pt/Cu/Ni	0.004/0.10	60/0.42	599/315	710/216	21.1	0.647/1.64	0.806
EF-14	Aluminum	0.002/0.05	60/0.42	600/316	746/227	28.6	1.155/2.93	2.547
EF-71	Aluminum	0.003/0.08	60/0.42	599/315	746/227	49.1	0.820/2.08	0.947
Environmental Condition No. 12								
AB-15	Baseline	N/A	80/0.56	602/317	767/234	92.3	1.845/4.69	0.690
AB-16	Baseline	N/A	80/0.56	600/316	764/233	90.7	1.707/4.33	1.097
EP-4	Pt/Cu/Ni	0.002/0.05	80/0.56	599/315	746/227	40.7	0.976/2.48	1.325
EP-5	Pt/Cu/Ni	0.002/0.05	80/0.56	598/314	742/226	31.8	1.618/4.11	2.475
EF-15	Aluminum	0.002/0.05	80/0.56	600/316	765/233	48.0	1.454/3.69	0.621
EF-16	Aluminum	0.002/0.05	80/0.56	603/317	755/230	47.1	1.050/2.67	0.851

*No. 1 specimen ignition below visibility range.
**No. 2 burn through below visibility range.

APPENDIX A. COMBUSTION DATA FOR SUBSTRATE: Ti 3Al-6Cr-8V-0.4Mo-4Zr (Continued)

Specimen No.	*Coating Type*	*Coating Thickness (in./mm)*	*Chamber Pressure (psia/MPa)*	*Chamber Temperature (°F/°C)*	*Air Velocity (ft/sec/m/sec)*	*Burn Severity (%)*	*Chordwise Burn Velocity (in./sec/cm/sec)*	*Ignition Time (sec)*
Environmental Condition No. 13								
AB-17	Baseline	N/A	40/0.28	723/384	766/233	90.0	0.852/2.16	2.990
EP-6	Pt/Cu/Ni	0.002/0.05	40/0.28	722/383	721/220	4.1	N/A	N/A
EP-18	Pt/Cu/Ni	0.004/0.10	40/0.28	724/384	754/230	3.3	N/A	N/A
EF-17	Aluminum	0.002/0.05	40/0.28	723/384	766/233	35.6	0.788/2.00	3.596
EF-72	Aluminum	0.003/0.08	40/0.28	723/384	766/233	43.4	0.6[illegible]/1.55	2.578
Environmental Condition No. 14								
AB-18	Baseline	N/A	60/0.42	723/384	776/237	90.6	1.407/3.57	0.832
AB-19	Baseline	N/A	60/0.42	724/384	777/237	92.5	1.428/3.63	0.965
EP-7	Pt/Cu/Ni	0.002/0.05	60/0.42	725/385	753/230	35.8	0.850/2.16	0.825
EP-9	Pt/Cu/Ni	0.002/0.05	60/0.42	722/383	751/229	35.3	0.990/2.51	0.955
EF-18	Aluminum	0.002/0.05	60/0.42	725/385	781/238	52.8	0.801/2.03	6.574
EF-19	Aluminum	0.002/0.05	60/0.42	725/385	781/238	45.0	1.185/3.01	0.853
Environmental Condition No. 15								
AB-20	Baseline	N/A	80/0.56	724/384	772/235	93.7	1.896/4.82	0.799
EP-10	Pt/Cu/Ni	0.002/0.05	80/0.56	724/384	745/227	40.2	1.677/4.26	0.820
EP-19	Pt/Cu/Ni	0.004/0.10	80/0.56	725/385	749/228	36.6	1.772/4.50	0.776
EF-20	Aluminum	0.002/0.05	80/0.56	725/385	739/225	54.2	1.891/4.80	0.540
EF-73	Aluminum	0.003/0.08	80/0.56	725/385	749/228	51.8	1.767/4.49	0.803
Environmental Condition No. 16								
AB-21	Baseline	N/A	40/0.28	825/441	753/230	91.5	***	***
AB-22	Baseline	N/A	40/0.28	824/440	752/229	89.8	1.093/2.79	3.293
EP-11	Pt/Cu/Ni	0.002/0.05	40/0.28	824/440	751/229	29.1	0.561/1.42	1.757
EP-12	Pt/Cu/Ni	0.002/0.05	40/0.28	823/439	752/229	20.0	0.447/1.14	3.909
EF-21	Aluminum	0.002/0.05	40/0.28	825/441	752/229	44.0	0.769/1.95	1.234
EF-22	Aluminum	0.002/0.05	40/0.28	824/440	752/229	44.6	0.835/2.12	1.181
Environmental Condition No. 17								
AB-23	Baseline	N/A	60/0.42	825/441	770/235	92.7	1.675/4.25	0.823
EP-14	Pt/Cu/Ni	0.002/0.05	60/0.42	827/442	768/234	29.0	0.971/2.47	1.453
EP-20	Pt/Cu/Ni	0.004/0.10	60/0.42	827/442	777/237	31.7	1.058/2.69	0.715
EF-23	Aluminum	0.002/0.05	60/0.42	826/441	758/231	51.7	1.349/3.43	0.635
EF-74	Aluminum	0.003/0.08	60/0.42	827/442	758/231	46.9	1.242/3.15	0.803
Environmental Condition No. 18								
AB-24	Baseline	N/A	80/0.56	828/442	781/238	92.0	2.628/6.68	0.623
EP-47	Pt/Cu/Ni	0.002/0.05	80/0.56	824/440	772/235	57.7	2.195/5.58	0.509
EP-21	Pt/Cu/Ni	0.004/0.10	80/0.56	828/442	767/234	15.4	0.773/1.96	1.473
EF-24	Aluminum	0.002/0.05	80/0.56	825/441	773/236	57.4	1.829/4.65	0.489
EF-75	Aluminum	0.003/0.08	80/0.56	827/442	773/236	66.4	1.904/4.84	0.708

***No. 3 film destroyed in processing.

APPENDIX A. COMBUSTION DATA FOR SUBSTRATE: Ti 3Al-6Cr-8V-0.4Mo-4Zr (Continued)

Specimen No.	Coating Type	Coating Thickness (in./mm)	Chamber Pressure (psia/MPa)	Chamber Temperature (°F/°C)	Air Velocity (ft/sec/m/sec)	Burn Severity (%)	Chordwise Burn Velocity (in./sec/cm/sec)	Ignition Time (sec)
Environmental Condition No. 19								
AB-5	Baseline	N/A	40/0.28	603/317	932/284	72.1	0.932/2.37	0.943
AB-6	Baseline	N/A	40/0.28	593/312	914/279	30.0	0.921/2.34	2.308
EP-57	Pt/Cu/Ni	0.002/0.05	40/0.28	600/316	884/269	45.8	0.752/1.91	1.307
EP-58	Pt/Cu/Ni	0.002/0.05	40/0.28	598/314	853/260	<1.0	N/A	N/A
EF-1	Aluminum	0.002/0.05	40/0.28	602/317	916/279	29.5	0.736/1.87	1.272
EF-2	Aluminum	0.002/0.05	40/0.28	597/314	893/272	30.0	0.781/1.98	1.333
Environmental Condition No. 20								
AB-7	Baseline	N/A	60/0.42	602/317	932/284	72.5	1.467/3.73	1.034
EP-59	Pt/Cu/Ni	0.002/0.05	60/0.42	599/315	856/261	45.8	1.361/3.46	2.362
EP-30	Pt/Cu/Ni	0.004/0.10	60/0.42	600/316	838/255	51.4	0.938/2.38	1.222
EF-3	Aluminum	0.002/0.05	60/0.42	603/317	888/271	27.4	1.214/3.08	0.777
EF-64	Aluminum	0.003/0.08	60/0.42	604/318	929/283	47.5	1.201/3.05	0.884
Environmental Condition No. 21								
AB-8	Baseline	N/A	80/0.56	603/317	919/280	73.5	2.602/6.61	0.648
EP-60	Pt/Cu/Ni	0.002/0.05	80/0.56	602/317	861/262	45.8	2.304/5.85	0.478
EP-31	Pt/Cu/Ni	0.004/0.10	80/0.56	598/314	841/256	38.6	2.303/5.85	1.218
EF-4	Aluminum	0.002/0.05	80/0.56	603/317	891/272	44.4	1.778/4.52	0.839
EF-65	Aluminum	0.003/0.08	80/0.56	607/319	898/274	50.6	1.814/4.61	0.456
Environmental Condition No. 22								
AB-9	Baseline	N/A	40/0.28	726/386	965/294	71.9	0.744/1.89	2.041
EP-61	Pt/Cu/Ni	0.002/0.05	40/0.28	728/387	826/252	36.7	0.704/1.79	1.571
EP-32	Pt/Cu/Ni	0.004/0.10	40/0.28	725/385	856/261	1.3	N/A	N/A
EF-5	Aluminum	0.002/0.05	40/0.28	724/384	897/273	36.0	0.905/2.30	0.991
EF-66	Aluminum	0.003/0.08	40/0.28	728/387	899/274	32.7	*	*
Environmental Condition No. 23								
AB-4	Baseline	N/A	60/0.42	727/386	918/280	95.3	1.919/4.87	0.890
EP-62	Pt/Cu/Ni	0.002/0.05	60/0.42	724/384	883/269	39.3	1.071/2.72	1.953
EP-33	Pt/Cu/Ni	0.004/0.10	60/0.42	726/386	885/270	43.5	1.525/3.87	0.698
EF-6	Aluminum	0.002/0.05	60/0.42	726/386	900/274	52.3	1.553/3.94	0.540
EF-67	Aluminum	0.003/0.08	60/0.42	726/386	919/280	53.2	***	***
Environmental Condition No. 24								
AB-3	Baseline	N/A	80/0.56	728/387	930/283	73.5	2.576/6.54	0.794
AB-10	Baseline	N/A	80/0.56	725/385	904/276	73.0	2.798/7.11	0.517
EP-71	Pt/Cu/Ni	0.002/0.05	80/0.56	723/384	949/289	67.3	1.771/4.50	0.909
EP-85	Pt/Cu/Ni	0.002/0.05	80/0.56	724/384	953/290	70.8	1.745/4.43	0.674
EF-7	Aluminum	0.002/0.05	80/0.56	723/384	899/274	41.8	2.138/5.43	0.459
EF-8	Aluminum	0.002/0.05	80/0.56	727/386	896/273	37.7	2.115/5.37	0.674

***Film destroyed in processing.

APPENDIX A. COMBUSTION DATA FOR SUBSTRATE: Ti 3Al-6Cr-8V-0.4Mo-4Zr (Continued)

Specimen No.	Coating Type	Coating Thickness (in./mm)	Chamber Pressure (psia/MPa)	Chamber Temperature (°F/°C)	Air Velocity (ft/sec/m/sec)	Burn Severity (%)	Chordwise Burn Velocity (in./sec/cm/sec)	Ignition Time (sec)
Environmental Condition No. 25								
AB-11	Baseline	N/A	40/0.28	827/442	924/282	49	1.158/2.94	0.687
EP-86	Pt/Cu/Ni	0.002/0.05	40/0.28	822/439	924/282	53	NA*	NA*
EP-34	Pt/Cu/Ni	0.004/0.10	40/0.28	827/442	921/281	3	0.436/1.11	2.535
EF-9	Aluminum	0.002/0.05	40/0.28	824/440	922/281	33	0.950/2.41	0.668
EF-68	Aluminum	0.003/0.08	40/0.28	824/440	923/281	43	0.875/2.22	0.335
Environmental Condition No. 26								
AB-2	Baseline	N/A	60/0.42	825/441	988/301	76	2.110/5.36	0.715
AB-12	Baseline	N/A	60/0.42	827/442	930/283	71	2.172/5.52	0.687
EP-87	Pt/Cu/Ni	0.002/0.05	60/0.42	827/442	922/281	56	NA*	NA*
EP-88	Pt/Cu/Ni	0.002/0.05	60/0.42	827/442	917/280	43	1.283/3.26	0.627
EF-10	Aluminum	0.002/0.05	60/0.42	826/441	916/279	36	2.143/5.44	0.662
EF-11	Aluminum	0.002/0.05	60/0.42	825/441	906/276	42	1.544/3.92	0.660
Environmental Condition No. 27								
AB-1	Baseline	N/A	80/0.56	827/442	979/298	79	2.606/6.62	1.028
EP-89	Pt/Cu/Ni	0.002/0.05	80/0.56	825/441	926/282	66	2.262/5.75	1.223
EP-36	Pt/Cu/Ni	0.004/0.10	80/0.56	825/441	927/283	30	2.297/5.83	2.564
EF-12	Aluminum	0.002/0.05	80/0.56	826/441	906/276	66	2.353/5.98	0.467
EF-69	Aluminum	0.003/0.08	80/0.56	826/441	949/289	54	2.216/5.63	0.594

*No. 1 specimen ignition below visibility range.

APPENDIX B. COMBUSTION DATA FOR SUBSTRATE: Ti 8Al-1Mo-1V

Specimen No.	Coating Type	Coating Thickness (in./mm)	Chamber Pressure (psia/MPa)	Chamber Temperature (°F/°C)	Air Velocity (ft/sec/m/sec)	Burn Severity (%)	Chordwise Burn Velocity (in./sec/cm/sec)	Ignition Time (sec)
Environmental Condition No. 1								
EB-23	Baseline	N/A	40/0.28	600/316	578/176	50	0.531/1.35	0.707
EC-2	Pt/Cu/Ni	0.002/0.05	40/0.28	600/316	575/175	2.3	N/A	N/A
EC-46	Pt/Cu/Ni	0.004/0.10	40/0.28	600/316	572/174	<1	N/A	N/A
EA-21	Aluminum	0.002/0.05	40/0.28	600/316	587/179	<1	N/A	N/A
EA-51	Aluminum	0.003/0.08	40/0.28	600/316	587/179	<1	N/A	N/A
Environmental Condition No. 2								
EB-8	Baseline	N/A	60/0.42	600/316	426/130	94	0.741/1.88	1.855
EB-7	Baseline	N/A	60/0.42	600/316	435/133	96	0.655/1.66	0.254
EC-14	Pt/Cu/Ni	0.002/0.05	60/0.42	600/316	426/130	20	0.534/1.36	2.201
EC-13	Pt/Cu/Ni	0.002/0.05	60/0.42	600/316	426/130	<1	N/A	N/A
EA-22	Aluminum	0.002/0.05	60/0.42	600/316	579/176	35	1.064/2.70	1.215
EA-23	Aluminum	0.002/0.05	60/0.42	600/316	598/182	29	1.160/2.95	2.010
Environmental Condition No. 3								
EB-24	Baseline	N/A	80/0.56	600/316	590/180	98	1.442/3.66	0.974
EC-10	Pt/Cu/Ni	0.002/0.05	80/0.56	600/316	584/178	93	1.266/3.22	0.625
EC-47	Pt/Cu/Ni	0.004/0.10	80/0.56	600/316	590/180	49	1.285/3.26	0.798
EA-24	Aluminum	0.002/0.05	80/0.56	600/316	597/182	41	1.421/3.61	1.161
EA-52	Aluminum	0.003/0.08	80/0.56	600/316	600/183	36	1.336/3.39	2.882
Environmental Condition No. 4								
EB-25	Baseline	N/A	40/0.28	725/385	609/186	98	0.728/1.85	1.726
EB-26	Baseline	N/A	40/0.28	724/384	622/190	98	0.645/1.64	1.481
EC-35	Pt/Cu/Ni	0.002/0.05	40/0.28	722/383	608/185	76	0.526/1.34	1.629
EC-39	Pt/Cu/Ni	0.002/0.05	40/0.28	724/384	609/186	50	0.437/1.11	2.048
EA-25	Aluminum	0.002/0.05	40/0.28	723/384	615/187	<1	N/A	N/A
EA-26	Aluminum	0.002/0.05	40/0.28	722/383	614/187	34	1.085/2.76	4.420
Environmental Condition No. 5								
EB-11	Baseline	N/A	60/0.42	725/385	541/165	94	0.593/1.51	1.212
EC-37	Pt/Cu/Ni	0.002/0.05	60/0.42	725/385	706/215	64	0.978/2.48	1.339
EC-48	Pt/Cu/Ni	0.004/0.10	60/0.42	724/384	701/214	44	0.865/2.20	1.139
EA-27	Aluminum	0.002/0.05	60/0.42	725/385	617/188	37	1.184/3.01	3.091
EA-53	Aluminum	0.003/0.08	60/0.42	724/384	617/188	34	0.928/2.36	1.424
Environmental Condition No. 6								
EB-27	Baseline	N/A	80/0.56	726/386	611/186	97	1.520/3.86	0.727
EC-32	Pt/Cu/Ni	0.002/0.05	80/0.56	724/384	621/189	77	1.236/3.14	0.791
EC-49	Pt/Cu/Ni	0.004/0.10	80/0.56	724/384	621/189	84	1.305/3.31	0.809
EA-28	Aluminum	0.002/0.05	80/0.56	725/385	631/192	65	1.207/3.07	1.609
EA-54	Aluminum	0.003/0.08	80/0.56	725/385	625/190	38	1.290/3.28	2.214

APPENDIX B. COMBUSTION DATA FOR SUBSTRATE: Ti 8Al-1Mo-1V (Continued)

Specimen No.	*Coating Type*	*Coating Thickness (in./mm)*	*Chamber Pressure (psia/MPa)*	*Chamber Temperature (°F/°C)*	*Air Velocity (ft/sec/m/sec)*	*Burn Severity (%)*	*Chordwise Burn Velocity (in./sec/cm/sec)*	*Ignition Time (sec)*
Environmental Condition No. 7								
EB-40	Baseline	N/A	40/0.28	823/439	647/197	76	0.607/1.54	2.741
EC-77	Pt/Cu/Ni	0.002/0.05	40/0.28	824/440	648/198	29	0.649/1.65	2.331
EC-69	Pt/Cu/Ni	0.004/0.10	40/0.28	823/439	640/195	<1	N/A	N/A
EA-29	Aluminum	0.002/0.05	40/0.28	822/439	648/198	35	0.606/1.54	7.255
EA-55	Aluminum	0.003/0.08	40/0.28	824/440	641/196	<1	N/A	N/A
Environmental Condition No. 8								
EB-41	Baseline	N/A	60/0.42	823/439	647/197	78	1.132/2.88	0.760
EC-79	Pt/Cu/Ni	0.002/0.05	60/0.42	823/439	670/204	64	1.110/2.82	0.710
EC-70	Pt/Cu/Ni	0.004/0.10	60/0.42	823/439	647/197	45	1.120/2.84	2.094
EA-30	Aluminum	0.002/0.05	60/0.42	823/439	647/197	17	0.948/2.41	0.746
EA-56	Aluminum	0.003/0.08	60/0.42	804/429	637/194	41	0.971/2.47	2.078
Environmental Condition No. 9								
EB-42	Baseline	N/A	80/0.56	826/441	667/203	80	1.529/3.88	0.629
EB-43	Baseline	N/A	80/0.56	823/439	664/202	78	1.527/3.88	1.064
EC-67	Pt/Cu/Ni	0.002/0.05	80/0.56	823/439	675/206	65	1.522/3.87	0.623
EC-80	Pt/Cu/Ni	0.002/0.05	80/0.56	827/442	673/205	78	1.373/3.49	0.828
EA-31	Aluminum	0.002/0.05	80/0.56	828/442	662/202	43	1.490/3.78	0.428
EA-32	Aluminum	0.002/0.05	80/0.56	828/442	669/204	75	1.286/3.27	0.624
Environmental Condition No. 10								
EB-15	Baseline	N/A	40/0.28	599/315	740/226	95	0.811/2.06	1.297
EC-26	Pt/Cu/Ni	0.002/0.05	40/0.28	600/316	737/225	65	0.676/1.72	1.852
EC-55	Pt/Cu/Ni	0.004/0.10	40/0.28	600/316	729/222	9	N/A**	2.589
EA-9	Aluminum	0.002/0.05	40/0.28	599/315	700/213	42	0.809/2.05	2.138
EA-45	Aluminum	0.003/0.08	40/0.28	598/314	699/213	41	0.608/1.54	1.558
Environmental Condition No. 11								
EB-16	Baseline	N/A	60/0.42	601/316	743/226	96	1.197/3.04	1.067
EC-95	Pt/Cu/Ni	0.002/0.05	60/0.42	598/314	784/239	67	1.042/2.65	0.663
EC-50	Pt/Cu/Ni	0.004/0.10	60/0.42	600/316	750/229	46	0.939/2.39	1.003
EA-10	Aluminum	0.002/0.05	60/0.42	599/315	724/221	48	1.175/2.98	0.892
EA-46	Aluminum	0.003/0.08	60/0.42	599/315	742/226	46	1.056/2.68	1.468
Environmental Condition No. 12								
EB-17	Baseline	N/A	80/0.56	603/317	747/228	96	1.713/4.35	0.691
EB-18	Baseline	N/A	80/0.56	600/316	742/226	97	1.701/4.32	0.900
EC-24	Pt/Cu/Ni	0.002/0.05	80/0.56	600/316	737/225	74	1.639/4.16	0.470
EC-25	Pt/Cu/Ni	0.002/0.05	80/0.56	600/316	722/220		1.700/4.32	1.204
EA-11	Aluminum	0.002/0.05	80/0.56	600/316	727/222	91	1.565/3.98	1.038
EA-12	Aluminum	0.002/0.05	80/0.56	599/315	744/227	83	1.544/3.92	0.849

**No. 2 burn through below visibility range.

APPENDIX B. COMBUSTION DATA FOR SUBSTRATE: Ti 8Al-1Mo-1V (Continued)

Specimen No.	*Coating Type*	*Coating Thickness (in./mm)*	*Chamber Pressure (psia/MPa)*	*Chamber Temperature (°F/°C)*	*Air Velocity (ft/sec/m/sec)*	*Burn Severity (%)*	*Chordwise Burn Velocity (in./sec/cm/sec)*	*Ignition Time (sec)*
Environmental Condition No. 13								
EB-22	Baseline	N/A	40/0.28	724/384	752/229	95	0.834/2.12	1.183
EC-28	Pt/Cu/Ni	0.002/0.05	40/0.28	723/384	771/235	39	0.619/1.57	0.991
EC-51	Pt/Cu/Ni	0.004/0.10	40/0.28	724/384	753/230	62	0.506/1.29	0.698
EA-13	Aluminum	0.002/0.05	40/0.28	721/383	764/233	42	0.685/1.74	0.857
EA-47	Aluminum	0.003/0.08	40/0.28	723/384	747/228	94	0.608/1.54	1.863
Environmental Condition No. 14								
EB-20	Baseline	N/A	60/0.42	725/385	781/238	100	1.286/3.27	0.945
EB-21	Baseline	N/A	60/0.42	723/384	768/234	99	1.285/3.26	0.588
EC-29	Pt/Cu/Ni	0.002/0.05	60/0.42	724/384	781/238	53	N/A***	N/A***
EC-30	Pt/Cu/Ni	0.002/0.05	60/0.42	724/384	781/238	49	1.238/3.14	1.192
EB-14	Aluminum	0.002/0.05	60/0.42	723/384	752/229	89	1.218/3.09	0.921
EA-15	Aluminum	0.002/0.05	60/0.42	725/385	768/234	49	1.200/3.05	0.827
Environmental Condition No. 15								
EB-19	Baseline	N/A	80/0.56	726/386	788/240	93	1.868/4.74	0.717
EC-31	Pt/Cu/Ni	0.002/0.05	80/0.56	725/385	790/241	73	1.928/4.90	1.297
EC-52	Pt/Cu/Ni	0.004/0.10	80/0.56	726/386	763/233	85	1.693/4.30	0.866
EA-16	Aluminum	0.002/0.05	80/0.56	725/385	764/233	89	1.708/4.34	0.942
EA-17	Aluminum	0.003/0.08	80/0.56	725/385	791/241	57	1.559/3.96	0.764
Environmental Condition No. 16								
EB-36	Baseline	N/A	40/0.28	822/439	772/235	74	0.740/1.88	1.994
EB-37	Baseline	N/A	40/0.28	823/439	759/231	74	0.845/2.15	4.739
EC-72	Pt/Cu/Ni	0.002/0.05	40/0.28	821/438	779/237	40	0.609/1.55	1.092
EC-74	Pt/Cu/Ni	0.002/0.05	40/0.28	823/439	793/242	32	0.736/1.87	2.651
EA-17	Aluminum	0.002/0.05	40/0.28	823/439	759/231	89	1.076/2.73	3.176
EA-18	Aluminum	0.002/0.05	40/0.28	825/441	765/233	53	0.788/2.00	2.030
Environmental Condition No. 17								
EB-38	Baseline	N/A	60/0.42	824/440	799/244	76	1.313/3.34	0.883
EC-78	Pt/Cu/Ni	0.002/0.05	60/0.42	823/439	798/243	54	1.170/2.97	1.598
EC-60	Pt/Cu/Ni	0.004/0.10	60/0.42	823/439	798/243	50	1.073/2.73	2.545
EA-19	Aluminum	0.002/0.05	60/0.42	825/441	790/241	88	1.336/3.39	0.544
EA-49	Aluminum	0.003/0.08	60/0.42	824/440	771/235	58	1.212/3.08	1.041
Environmental Condition No. 18								
EB-39	Baseline	N/A	80/0.56	823/439	790/241	77	1.862/4.73	0.841
EC-27	Pt/Cu/Ni	0.002/0.05	80/0.56	848/453	819/250	89	2.123/5.39	1.017
EC-66	Pt/Cu/Ni	0.004/0.10	80/0.56	824/440	817/249	56	1.701/4.32	0.964
EA-20	Aluminum	0.002/0.05	80/0.[illegible]	824/440	780/238	88	1.865/4.74	1.311
EA-50	Aluminum	0.003/0.08	80/0.56	822/439	784/239	90	1.760/4.47	0.735

***No. 3 film destroyed in processing.

APPENDIX B. COMBUSTION DATA FOR SUBSTRATE: Ti 8Al-1Mo-1V (Continued)

Specimen No.	Coating Type	Coating Thickness (in./mm)	Chamber Pressure (psia/MPa)	Chamber Temperature (°F/°C)	Air Velocity (ft/sec/m/sec)	Burn Severity (%)	Chordwise Burn Velocity (in./sec/cm/sec)	Ignition Time (sec)
Environmental Condition No. 19								
EB-28	Baseline	N/A	40/0.28	606/319	892/272	95	0.928/2.36	1.039
EB-29	Baseline	N/A	40/0.28	598/314	782/238	36	0.805/2.04	1.497
EC-41	Pt/Cu/Ni	0.002/0.05	40/0.28	606/319	908/277	46	0.705/1.79	0.984
EC-61	Pt/Cu/Ni	0.002/0.05	40/0.28	574/301	787/240	20	0.650/1.65	1.882
EA-1	Aluminum	0.002/0.05	40/0.28	606/319	891/272	49	0.666/1.69	0.995
EA-4	Aluminum	0.002/0.05	40/0.28	598/314	803/245	51	0.675/1.71	0.736
Environmental Condition No. 20								
EB-30	Baseline	N/A	60/0.42	600/316	793/242	100	1.355/3.44	0.706
EC-42	Pt/Cu/Ni	0.002/0.05	60/0.42	602/317	863/263	54	1.286/3.27	0.757
EC-53	Pt/Cu/Ni	0.004/0.10	60/0.42	600/316	873/266	51	1.300/3.30	0.694
EA-2	Aluminum	0.002/0.05	60/0.42	603/317	872/266	96	1.184/3.01	0.522
EA-40	Aluminum	0.003/0.08	60/0.42	603/317	915/279	82	1.242/3.15	0.731
Environmental Condition No. 21								
EB-31	Baseline	N/A	80/0.56	601/316	793/242	98	1.905/4.84	0.583
EC-43	Pt/Cu/Ni	0.002/0.05	80/0.56	602/317	787/240	56	1.767/4.49	0.545
EC-56	Pt/Cu/Ni	0.004/0.10	80/0.56	603/317	854/260	43	1.848/4.69	0.870
EA-3	Aluminum	0.002/0.05	80/0.56	604/318	920/280	56	1.786/4.54	0.463
EA-41	Aluminum	0.003/0.08	80/0.56	604/318	920/280	61	1.689/4.29	0.735
Environmental Condition No. 22								
EB-32	Baseline	N/A	40/0.28	725/385	805/245	82	0.661/1.68	0.636
EC-62	Pt/Cu/Ni	0.002/0.05	40/0.28	720/382	808/246	26	0.694/1.76	1.740
EC-57	Pt/Cu/Ni	0.004/0.10	40/0.28	724/384	800/244	50	0.792/2.01	1.887
EA-5	Aluminum	0.002/0.05	40/0.28	725/385	929/283	61	1.366/3.47	0.943
EA-42	Aluminum	0.003/0.08	40/0.28	722/383	965/294	51	0.993/2.52	0.931
Environmental Condition No. 23								
EB-33	Baseline	N/A	60/0.42	726/386	803/245	95	1.300/3.30	0.629
EC-63	Pt/Cu/Ni	0.002/0.05	60/0.42	725/385	824/251	82	1.252/3.18	0.673
EC-58	Pt/Cu/Ni	0.004/0.10	60/0.42	726/386	822/251	54	1.256/3.19	1.334
EA-6	Aluminum	0.002/0.05	60/0.42	722/383	989/301	91	0.793/2.01	1.888
EA-44	Aluminum	0.003/0.08	60/0.42	725/385	972/296	71	1.299/3.30	0.591
Environmental Condition No. 24								
EB-34	Baseline	N/A	80/0.56	713/378	978/298	98	2.246/5.70	0.613
EB-35	Baseline	N/A	80/0.56	725/385	992/302	95	2.277/5.78	0.800
EC-64	Pt/Cu/Ni	0.002/0.05	80/0.56	727/386	835/255	45	1.854/4.71	0.543
EC-65	Pt/Cu/Ni	0.002/0.05	80/0.56	727/386	827/252	93	1.842/4.68	0.619
EA-7	Aluminum	0.002/0.05	80/0.56	728/387	951/290	60	2.028/5.15	0.686
EA-8	Aluminum	0.002/0.05	80/0.56	727/386	967/295	94	1.916/4.87	0.838

APPENDIX B. COMBUSTION DATA FOR SUBSTRATE: Ti 8Al-1Mo-1V (Continued)

Specimen No.	Coating Type	Coating Thickness (in./mm)	Chamber Pressure (psia/MPa)	Chamber Temperature (°F/°C)	Air Velocity (ft/sec/m/sec)	Burn Severity (%)	Chordwise Burn Velocity (in./sec/cm/sec)	Ignition Time (sec)
Environmental Condition No. 25								
EB-44	Baseline	N/A	40/0.28	826/441	962/293	74	0.880/2.24	1.095
EC-71	Pt/Cu/Ni	0.002/0.05	40/0.28	822/439	1021/311	65	0.879/2.23	1.053
EC-59	Pt/Cu/Ni	0.004/0.10	40/0.28	823/439	1007/307	69	1.063/2.70	0.923
EA-33	Aluminum	0.002/0.05	40/0.28	827/442	944/288	88	0.728/1.85	1.001
EA-76	Aluminum	0.003/0.08	40/0.28	823/439	1026/313	70	0.988/2.51	4.245
Environmental Condition No. 26								
EB-45	Baseline	N/A	60/0.42	826/441	970/296	75	1.699/4.32	0.628
EB-46	Baseline	N/A	60/0.42	828/442	958/292	75	1.698/4.31	0.706
EC-68	Pt/Cu/Ni	0.002/0.05	60/0.42	819/437	1029/314	76	1.456/3.70	0.654
EC-93	Pt/Cu/Ni	0.002/0.05	60/0.42	825/441	1044/318	80	1.689/4.29	0.510
EA-34	Aluminum	0.002/0.05	60/0.42	823/439	962/293	100	1.477/3.75	0.592
EA-35	Aluminum	0.002/0.05	60/0.42	825/441	976/297	96	1.389/3.53	0.523
Environmental Condition No. 27								
EB-47	Baseline	N/A	80/0.56	827/442	993/303	89	2.297/5.83	0.620
EC-94	Pt/Cu/Ni	0.002/0.05	80/0.56	826/441	1016/310	82	2.227/5.66	2.695
EC-76	Pt/Cu/Ni	0.004/0.10	80/0.56	826/441	1030/314	68	1.960/4.98	3.177
EA-36	Aluminum	0.002/0.05	80/0.56	824/440	1019/311	74	2.312/5.87	1.066
EA-58	Aluminum	0.003/0.08	80/0.56	825/441	1020/311	74	1.775/4.51	0.728

APPENDIX C. COMBUSTION DATA FOR ADDITIONAL SPECIMENS TESTED

No. Specimen	Coating Type	Coating Thickness[1]		Chamber Pressure		Nominal Chamber Temperature		Nominal Air Velocity		% Burn Severity	Chordwise Burn Velocity	
		mm	(in.)	MPa	(psia)	°C	(°F)	m/sec	(ft/sec)		cm/sec	(in./sec)
CA-24	Cu/Al	0.05	0.002	0.42	60	316	600	244	800	36.3	3.23	1.270
CA-21	Cu/Al	0.11	0.0043	0.42	60	316	600	244	800	39.8	2.68	1.056
CA-25	Cu/Al	0.14	0.0055	0.42	60	316	600	244	800	35.5	(2)	(2)
CA-23	Cu/Al	0.20	0.008	0.42	60	316	600	244	800	29.3	3.82	1.505
NA-8	Ni/Al	0.05	0.002	0.42	60	316	600	244	800	47.4	(2)	(2)
NA-2	Ni/Al	0.10	0.004	0.42	60	316	600	244	800	62.5	1.53	0.602
NA-1	Ni/Al	0.15	0.006	0.42	60	316	600	244	800	89.5	1.72	0.677
Ti Al	None	NA	NA	0.55	80	316	600	244	800	0	NA	NA
Ti Al	None	NA	NA	0.62	90	316	600	244	800	0	NA	NA
Ti Al	None	NA	NA	0.69	100	316	600	244	800	0	NA	NA

1. All aluminum coatings were 0.05 (0.002) mm (in.) thick. Thickness shown in this column is for the copper or nickel component of the duplex coating.

2. Film usefulness destroyed during processing.

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